Chapter 9
Energy Conservation

9.1 Energy Conservation and Recovery

Energy conservation mainly refers to reducing energy consumption and increasing efficiency in energy usage. Energy conservation may lead to increased security, financial gain, and environmental protection. For example, electric motors consume a considerable amount of electrical energy and operate at efficiencies between 70 and 90%. Therefore, using an electric motor operating with higher efficiency will conserve energy throughout its useful life. Energy recovery leads to reducing the energy input by reducing the overall waste energy from a system. For example, a waste energy, mainly in the form of sensible or latent heat, from a subsystem may be usable in another part of the same system. Therefore, energy recovery may be a part of energy conservation. There is a large potential for energy recovery in industries and utilities leading to reduced use of fossil fuels and emission of CO_2 and NO_x. Some examples of energy recovery are:

- Hot water from processes such as power plants and steel mills may be used for heating of homes and offices in the nearby area. Energy conservation through insulation or improved buildings may also help. Low temperature heat recovery would be more effective for a short distance from producer to consumer.
- Regenerative brake is used in electric cars and trains, where the part of kinetic energy is recovered and stored as chemical energy in a battery.
- Active pressure reduction systems where the differential pressure in a pressurized fluid flow is recovered rather than converted to heat in a pressure reduction valve.
- Energy recycling.
- Water heat recycling.
- Heat recovery steam generator.
- Heat regenerative cyclone engine.

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- Thermal diode.
- Thermoelectric modules.

9.2 Conservation of Energy in Industrial Processes

Most of the industrial processes depend on stable and affordable energy supply to be competitive. Some of these industrial processes produce energy, while others use energy. For example, a Rankine engine produces electricity and compressors use it. Energy conservation in both types of processes will increase thermal efficiency and reduce wasted energy. The following sections discuss some possible process improvements that may lead to energy conservation in power production and compressor work.

9.2.1 Energy Conservation in Power Production

Section 6.7 discusses some possible modifications in improving the efficiency of power plants. Here, some examples underline the importance of energy conservation in Rankine cycle and Brayton cycle. In a Brayton cycle operating as gas-turbine engine, the temperature of the exhaust gas leaving the turbine T_4 is often higher than the temperature of the gas leaving the compressor T_2 as seen in Fig. 9.1. Therefore, the gas leaving the compressor can be heated in a regenerator by the hot exhaust gases as shown in Fig. 9.1b. Regenerator is a counter-flow heat exchanger, which is also known as *recuperator*, and recovers waste heat. The thermal efficiency of the Brayton cycle increases as a result of regeneration because the portion of energy of the exhaust gases is used to preheat the gas entering to the combustion chamber. Thus, in turn, regeneration can reduce the fuel input required for the same net work output from the cycle. The addition of a regenerator (operating without thermal losses) does not affect the net work output of the cycle. A regenerator with higher effectiveness will conserve more fuel. The effectiveness ε of the regenerator operating under adiabatic conditions is defined by

$$\varepsilon = \left(\frac{H_5 - H_2}{H_4 - H_2}\right) \tag{9.1}$$

The enthalpies H_i are shown in Fig. 9.1b. Under the cold-air standard temperature assumptions (Chap. 7.8.1), the effectiveness ε of the regenerator is defined approximately by

$$\varepsilon \simeq \left(\frac{T_5 - T_2}{T_4 - T_2}\right) \tag{9.2}$$

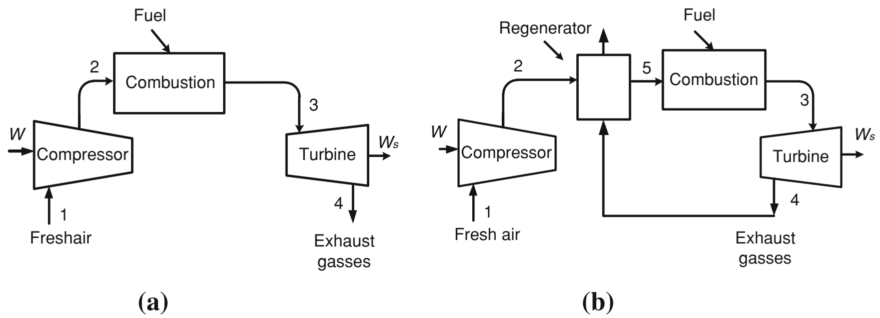


Fig. 9.1 **a** Simple Brayton cycle. **b** Brayton cycle with regeneration; the condition for regeneration is $T_4 > T_2$

The regeneration is possible only when $T_4 \gg T_2$. The effectiveness of most regenerators used in practical engine operations is below 0.85 [7].

Under the cold-air standard temperature assumptions, thermal efficiency of an ideal Brayton cycle with regeneration depends on the ratio of minimum to maximum temperatures and the pressure ratio, and estimated by

$$\eta_{\text{th.regen.}} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(\gamma-1)/\gamma} \tag{9.3}$$

where r_p is the compression ratio (P_2/P_1) and $\gamma = C_p/C_v$.

Example 9.1 Energy conservation by regeneration in a Brayton cycle

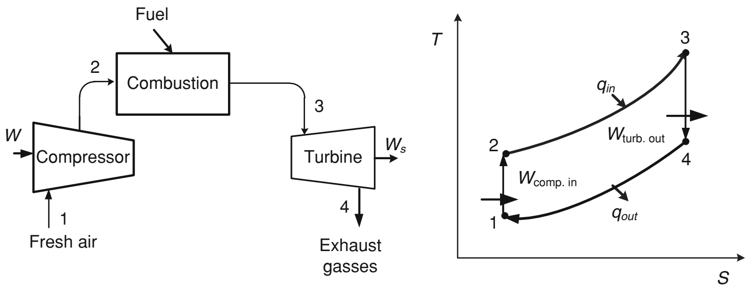
A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 9$. The fresh air temperature at the compressor inlet is 295 K. The air temperature at the inlet of the turbine is 1,300 K. The cycle operates with a compressor efficiency of 80% and a turbine efficiency of 80%. The unit cost of fuel is \$0.14/kWh. The cycle operates 360 days per year.

(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.
(b) If the power plant operates with a regenerator with an effectiveness of 0.78, determine the thermal efficiency of the cycle and annual conservation of fuel.

Solution:
Assume that the cycle is at steady-state flow and the changes in kinetic and potential energies are negligible. Heat capacity of the air is temperature dependent, and the air is an ideal gas.

(a) Basis: 1 kg/s air.
$\eta_{\text{turb}} = 0.8$, $\eta_{\text{comp}} = 0.8$, $r_p = P_2/P_1 = 9$

Process 1-2: isentropic compression



Data from (Table D1):
$T_1 = 295$ K, $H_1 = 295.17$ kJ/kg, $P_{r1} = 1.3068$

P_r shows the relative pressure defined in Eq. (7.36).

$$\frac{P_{r2}}{P_{r1}} = \frac{P_2}{P_1} = r_p \rightarrow P_{r2} = (9)(1.3068) = 11.76$$

Approximate values from Table D1 for the compressor exit:
at $P_{r2} = 11.76$: $T_2 = 550$ K and $H_2 = 555.74$ kJ/kg

Process 3–4: isentropic expansion in the turbine as seen on the *TS* diagram above
$T_3 = 1{,}300$ K, $H_3 = 1{,}395.97$ kJ/kg, $P_4/P_3 = 1/r_p = 1/9$, $P_{r3} = 330.9$

$$\frac{P_{r4}}{P_{r3}} = \frac{P_4}{P_3} \rightarrow P_{r4} = \left(\frac{1}{9}\right)(330.9) = 36.76$$

Approximate values from Table D1 at the exit of turbine:
at $P_{r4} = 36.76$: $T_4 = 745$ K and $H_4 = 761.87$ kJ/kg

The work input to the compressor:

$$W_{\text{comp.in}} = \frac{H_2 - H_1}{\eta_{\text{comp}}} = \frac{(335.74 - 295.17)\,\text{kJ/kg}}{0.8} = 325.7\,\text{kJ/kg}$$

The work output of the turbine:

$$W_{\text{turb.out}} = \eta_{\text{turb}}(H_3 - H_4) = 0.8(1{,}395.97 - 761.87) = 507.3\ \text{kJ/kg}$$

The back work ratio r_{bw}: $r_{\text{bw}} = \dfrac{W_{\text{comp.in}}}{W_{\text{turb.out}}} = \dfrac{325.7}{507.3} = 0.64$

This shows that 64% of the turbine output has been used in the compressor.
Net work output: $W_{\text{net}} = W_{\text{out}} - W_{\text{in}} = (507.3 - 325.7)\,\text{kJ/kg} = 181.6\ \text{kJ/kg}$

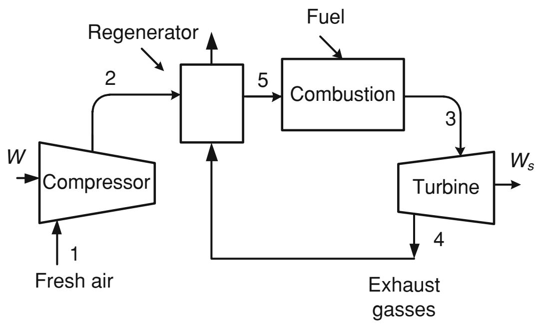
The actual air enthalpy at the compressor outlet:
$H_{2\text{a}} = H_1 + W_{\text{comp.in}} = (295.17 + 325.70)\,\text{kJ/kg} = 620.87\ \text{kJ/kg}$
The amount of heat added: $q_{\text{in}} = H_3 - H_{2a} = 1{,}395.97 - 620.87 = 775.1\ \text{kJ/kg}$
The thermal efficiency: $\eta_{\text{th}} = \dfrac{W_{\text{net}}}{q_{\text{in}}} = \dfrac{181.6}{775.1} = \mathbf{0.234\ or\ 23.4\%}$

The temperature of the exhaust air, T_4, and the actual enthalpy are estimated from the energy balance: $W_{\text{turb out}} = H_{4a} - H_3$

$H_{4a} = 1{,}395.97 - 507.3 = 888.67$ kJ/kg → $T_4 = 860$ K (From Table D1)

Advances in the compressor and turbine designs with minimal losses increase the efficiency of these components. In turn, a significant increase in the thermal efficiency of the cycle is possible.

(b) $T_4 = 860$ K and $T_2 = 550$ K, since $T_4 > T_2$ regeneration is possible. Regeneration with effectiveness of $\varepsilon = 0.78$:



$$\varepsilon = \left(\frac{H_5 - H_2}{H_4 - H_2}\right) = \frac{H_5 - 620.9}{888.67 - 620.9} = 0.78 \rightarrow H_5 = 829.80 \text{ kJ/kg}$$

$q_{in} = H_3 - H_5 = 1{,}395.97 - 829.8 = 566.2$ kJ/kg

This represents a conservation of 840.2 – 566.2 = 274.0 kJ/kg from the fuel required.

The thermal efficiency: $\eta_{th} = \dfrac{W_{net}}{q_{in}} = \dfrac{181.6}{566.2} = \mathbf{0.32 \text{ or } 32\%}$

Unit cost of fuel = \$0.14/kWh

Days of operation 360, hours of operation per year = 360(24) =8,640 h/year

Conserved fuel: (274 kJ/kg)(1 kg/s) (8,640 h/year) = 2,367,360 kWh/year

Saved money: (2,367,360 kWh/year) (\$0.14/kWh) = **\$331,430/year**

After the regeneration, the thermal efficiency has increased from 23 to 32% in the actual Brayton cycle operation. The addition of a regenerator (operating without thermal losses) does not affect the net work output of the cycle. Savings of fuel and costs are considerable.

9.2.1.1 Conservation of Energy by the Process Improvements

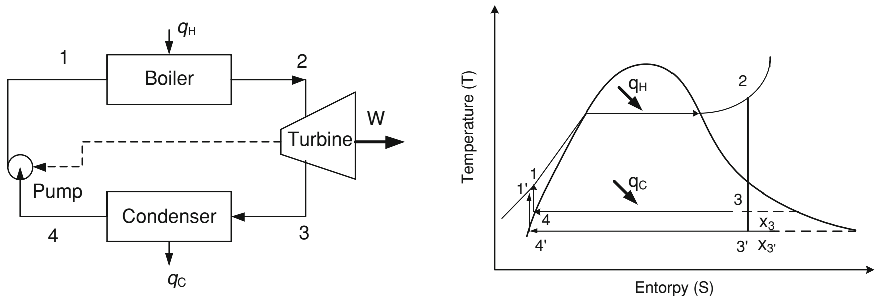
Some of the possible modifications in operation of steam power plants to increase the efficiency are [6, 5]:

- Increasing the efficiency of a Rankine cycle by reducing the condenser pressure. Example 9.2 illustrates the estimation of efficiency of a Rankine cycle operating at two different discharge pressures. The thermal efficiency increased from 27.6 to 33.4% by reducing the condenser pressure from 78.5 to 15.0 kPa. However the quality of the discharged steam decreased from 0.9 to 0.84, which is not desirable for the blades of the turbine. Savings are considerable since the power output increased. Example 9.3 compares the actual thermal efficiency with the maximum thermal efficiency obtained from fully reversible Carnot cycle.
- Increasing the efficiency of a Rankine cycle by increasing the boiler pressure. Example 9.4 illustrates the estimation of thermal efficiency of a Rankine cycle operating at a higher pressure. The thermal efficiency increased from 0.276 to 0.326 by increasing the boiler pressure from 3,500 to 9,800 kPa. However the quality of the discharged steam decreased from 0.9 to 0.80, which is not desirable for the blades of the turbine.
- Increasing the efficiency of a Rankine cycle by increasing the boiler temperature. Example 9.5 illustrates the estimation of thermal efficiency of a Rankine cycle operating at a higher temperature. The thermal efficiency increased from 0.276 to 0.298 by increasing the boiler temperature from 400 to 525°C. The quality of the discharged steam increased from 0.9 to 0.96, which is desirable for the protection of the turbine blades. Example 9.6 compares the estimated thermal efficiency with the maximum thermal efficiency obtained from the fully reversible Carnot cyle.

Example 9.2 Increasing the efficiency of a Rankine cycle by reducing the condenser pressure

A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 3,500 kPa and 400°C. Discharge pressure of the steam from the turbine is 78.5 kPa.

(a) Determine the thermal efficiency of the cycle.
(b) If the pressure of the discharge steam is reduced to 15 kPa determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is $0.10/kWh.



Solution:
Assume that the cycle is at steady-state flow and the changes in kinetic and potential energy are negligible. Efficiency of pump and turbine is 100%.

(a) $\dot{m}_s = 20.0$ kg/s
Using the data from the Appendix: Tables F3 and F4
Superheated steam (Table F4):
$P_2 = P_1 = 3{,}500$ kPa, $H_2 = 3{,}224.2$ kJ/kg, $S_2 = 6.8443$ kJ/kg, $T_2 = 400$°C
Saturated steam (Table F3):
$P_3 = P_4 = 78.5$ kPa ($T_{sat} = 366.15$ K), $V_4 = 0.001038$ m^3/kg
$H_{3\text{sat vap}} = 2{,}665.0$ kJ/kg, $H_4 = H_{3\text{sat liq}} = 389.6$ kJ/kg
$S_{3\text{sat vap}} = 7.4416$ kJ/kg K, $S_{3\text{sat liq}} = 1.2271$ kJ/kg K
Basis: 1 kg/s steam.
With a pump efficiency of $\eta_{\text{pump}} = 100\%$

$$W_{p,\text{in}} = V_1(P_1 - P_4) = (0.001038)(3{,}500 - 78.5)\left(\frac{1\,\text{kJ}}{1\ \text{kPa m}^3}\right) = 3.55\,\text{kJ/kg}$$

$$H_1 = H_4 + W_{p,\text{in}} = 393.1\,\text{kJ/kg}$$

Isentropic process $S_1 = S_4$ and $S_3 = S_2$.

The quality of the discharged wet steam ($S_2 < S_{3\text{sat vap}}$): $6.8443 < 7.4416$
$x_3 = (6.8463 - 1.2271)/(7.4416 - 1.2271) = 0.90$
$H_3 = 389.6(1 - 0.90) + 2{,}665.0 \times 0.90 = 2{,}437.5\,\text{kJ/kg}$

Heat interactions:
$q_{\text{in}} = H_2 - H_1 = 3{,}224.2 - 393.1 = 2{,}831.1\ \text{kJ/kg}$
$q_{\text{out}} = H_3 - H_4 = 2{,}437.5 - 389.6 = 2{,}048.0\,\text{kJ/kg}$
The thermodynamic efficiency of the cycle: $\eta_{\text{th}} = 1 - \dfrac{q_{\text{out}}}{q_{\text{in}}} = \mathbf{0.276\ or\ 27.6\%}$
Therefore, the plant uses only 27.6% of the heat it received in the boiler.
Turbine work output:
$W_{\text{out}} = H_2 - H_3 = 3{,}224.2 - 2{,}437.5 = 786.7\ \text{kJ/kg}$
Net work output:
$W_{\text{net}} = (q_{\text{in}} - q_{\text{out}}) = (2{,}831.1 - 2{,}048.0) = 783.1\ \text{kJ/kg}$

(b) Steam properties (Table F3):
$P_3 = P_4 = 15$ kPa, $T_{sat} = 327.15$ K, $V_4 = 0.001014$ m^3/kg
$H_{3\text{sat vap}} = 2{,}599.2$ kJ/kg, $H_4 = H_{3\text{sat liq}} = 226.0$ kJ/kg,
$S_{3\text{sat vap}} = 8.0093$ kJ/kg K, $S_{3\text{sat liq}} = 0.7550$ kJ/kg K

With a pump efficiency of: $\eta_{\text{pump}} = 100\%$

$$W_{p,\text{in}} = V_1(P_1 - P_4) = (0.001014)(3{,}500 - 15)\left(\frac{1\,\text{kJ}}{1\ \text{kPa m}^3}\right) = 3.53\,\text{kJ/kg}$$

$$H_1 = H_4 + W_{p,\text{in}} = 226.0 + 3.53 = 229.5\ \text{kJ/kg}$$

Isentropic process $S_1 = S_4$ and $S_3 = S_2$.
The quality of the discharged wet steam ($S_3 < S_{3\text{sat vap}}$): $6.8443 < 8.0093$
$x_{3'} = (6.8443 - 0.7550)/(8.0093 - 0.7550) = 0.84$
$H_{3'} = 226.0(1 - 0.84) + 2{,}599.2 \times 0.84 = 2{,}219.5\ \text{kJ/kg}$

Heat interactions:
$q_{in} = H_2 - H_1 = 3,224.2 - 229.5 = 2,994.7$ kJ/kg
$q_{out} = H_{3'} - H_4 = 2,219.5 - 226.0 = 1,993.5$ kJ/kg
The thermal efficiency of the cycle: $\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = \mathbf{0.334\ or\ 33.4\%}$
Therefore, the plant uses only 33.4% of the heat it received in the boiler.
Turbine work output
$W_{out} = H_2 - H_{3'} = 3,224.2 - 2,219.5 = 1,004.7$ kJ/kg
Cycle work out:
$W_{net} = (q_{in} - q_{out}) = (2,994.7 - 1,993.5) = 1,001.2$ kJ/kg
For a 360 days of operation = (360)(24) = 8,640 h/year
The annual increase in the net power output:
(20 kg/s)(1,001.2 – 783.1) kJ/kg (8,640) h/year = 37,687,680 kWh/year
For a unit selling price of electricity of $0.1/kWh
Annual saving = **$3,768,768/year**

The thermal efficiency increased from 0.276 to 0.334 by reducing the condenser pressure from 78.5 to 15.0 kPa. However the quality of the discharged steam decreased from 0.9 to 0.84, which is not desirable for the blades of the turbine. Savings are considerable.

Example 9.3 Maximum possible efficiency calculation in Example 9.2
Estimate the maximum possible efficiency for parts (a) and (b) in Example 9.2 and compare them with those obtained in parts (a) and (b) in Example 9.2.

Solution:
(a) The thermal efficiency of a Carnot cycle operating between the same temperature limits: $T_{min} = T_3 = 366.15$ K and $T_{max} = T_2 = 673.15$ K

$$\eta_{th,\,Carnot} = 1 - \frac{T_{min}}{T_{max}} = 1 - \frac{366.15\ \text{K}}{673.15\ \text{K}} = \mathbf{0.456\ or\ 45.6\%}$$

The difference between the two efficiencies occurs because of the large temperature differences. The ratio of the efficiencies, $\eta_{th}/\eta_{th,\ Carnot} = 0.276/0.456 = 0.60$ shows that only 60% of the possible efficiency is achieved in the cycle.

(b) The thermal efficiency of a Carnot cycle operating between the same temperature limits: $T_{min} = T_{3'} = 327.15$ K and $T_{max} = T_2 = 673.15$ K

$$\eta_{th,\,Carnot} = 1 - \frac{T_{min}}{T_{max}} = 1 - \frac{327.15}{673.15} = \mathbf{0.514\ of\ 51.4\%}$$

The ratio of the efficiencies, $\eta_{th}/\eta_{th,\ Carnot} = 0.334/0.51 = 0.65$ shows that only 65% of the possible efficiency is achieved in the cycle.

Example 9.4 Increasing the efficiency of a Rankine cycle by increasing the boiler pressure

A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 3,500 kPa and 400°C. Discharge pressure of the steam from the turbine is 78.5 kPa.

(a) If the pressure of the boiler is increased to 9,800 kPa while maintaining the turbine inlet temperature at 400°C, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is $0.10/kWh.

Solution:

Assume that the cycle is at steady-state flow and the changes in kinetic and potential energies are negligible. Pump efficiency of $\eta_{\text{pump}} = 1$

Basis: 1 kg/s steam. Using the data from the Appendix: Tables F3 and F4
From Example 9.2 part a: $\eta_{\text{th}} = 0.276$ and $W_{\text{net}} = 783.1$ kJ/kg at 3500 kPa

(a) Superheated steam:
$P_2 = P_1 = 9{,}800$ kPa; $H_2 = 3{,}104.2$ kJ/kg: $S_2 = 6.2325$ kJ/kg K, $T_2 = 400$°C

Saturated steam:
$P_3 = P_4 = 78.5$ kPa, $T_{\text{sat}} = 366.15$ K, $V_4 = 0.001038$ m^3/kg (Table F3)
$H_{3\text{sat vap}} = 2{,}665.0$ kJ/kg; $H_4 = H_{3\text{sat liq}} = 389.6$ kJ/kg;
$S_{3\text{sat vap}} = 7.4416$ kJ/kg K; $S_{3\text{sat liq}} = 1.2271$ kJ/kg K

$$W_{p,\text{in}} = V_1(P_1 - P_4) = (0.001038)(9{,}800 - 78.5)\left(\frac{1\text{ kJ}}{1\text{ kPa m}^3}\right) = 10.1\text{ kJ/kg}$$

$$H_1 = H_4 + W_{p,\text{in}} = 389.6 + 10.1 = 399.7\text{ kJ/kg}$$

Isentropic process $S_1 = S_4$ and $S_3 = S_2$.
The quality of the discharged wet steam x_3: ($S_3 < S_{3\text{sat vap}}$): $6.2325 < 7.4416$
$x_3 = (6.2325 - 1.2271)/(7.4416 - 1.2271) = 0.80$
$H_3 = 389.6(1 - 0.8) + 2{,}665.0 \times 0.8 = 2{,}210.0\text{ kJ/kg}$

Heat interactions:
$q_{\text{in}} = H_2 - H_1 = 3{,}104.2 - 399.7 = 2{,}704.5\text{ kJ/kg}$
$q_{\text{out}} = H_3 - H_4 = 2{,}210.0 - 389.6 = 1{,}820.4\text{ kJ/kg}$
The thermodynamic efficiency of the cycle: $\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = \mathbf{0.326\text{ or }32.6\%}$

Therefore, the plant uses only 32.6% of the heat it received in the boiler.
The thermal efficiency increased from 0.276 to 0.326 by increasing the boiler pressure from 3,500 to 9,800 kPa. However, the quality of the discharged steam decreased from 0.9 to 0.80, which is not desirable for the blades of the turbine.

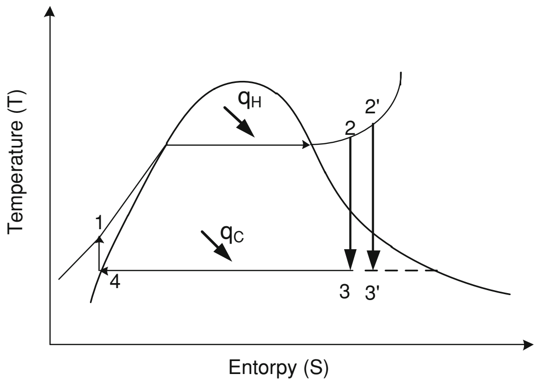
Turbine work output: $W_{\text{out}} = H_3 - H_2 = (3{,}104.2 - 2{,}210.0)\text{ kJ/kg} = 894.2\text{ kJ/kg}$
Cycle work out: $W_{\text{net}} = (q_{\text{in}} - q_{\text{out}}) = (2{,}704.5 - 1{,}820.4)\text{ kJ/kg} = 884.1\text{ kJ/kg}$

(b) $\dot{m}_s = 20.0$ kg/s,
For a 360 days of operation = (360)(24) = 8,640 h/year
The annual increase in the net power output:
(20 kg/s)(884.1 – 783.1) kJ/kg (8,640) h/year = 17,452,800 kWh/year
For a unit selling price of electricity of $0.1/kWh: annual saving = **$1,745,280**

Example 9.5 Increasing the efficiency of a Rankine cycle by increasing the boiler temperature

A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 3,500 kPa and 400°C. Discharge pressure of the steam from the turbine is 78.5 kPa.

(a) If the temperature of the boiler is increased to 525°C while maintaining the pressure at 3,500 kPa, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is \$0.10/kWh.



Solution:
Assume that the cycle is at steady-state flow and the changes in kinetic and potential energy are negligible.

(a) Basis: 1 kg/s steam. Using the data from the Appendix: Tables F3 and F4:

From Example 9.2 part a: $\eta_{th} = 0.276$ and $W_{net} = 783.1$ kJ/kg at 400°C
Superheated steam:
$P_2 = P_1 = 3{,}500$ kPa; $H_2 = 3{,}506.9$ kJ/kg: $S_2 = 7.2297$ kJ/kg, $T_2 = 525$°C
Saturated steam:
$P_3 = P_4 = 78.5$ kPa, $T_{sat} = 366.15$ K, $V_4 = 0.001038$ m^3/kg (Table F3)
$H_{3\text{sat vap}} = 2{,}665.0$ kJ/kg, $H_{3\text{sat liq}} = 389.6$ kJ/kg, $S_{3\text{sat vap}} = 7.4416$ kJ/kg K,
$S_{3\text{sat liq}} = 1.2271$ kJ/kg K

$$W_{p,\text{in}} = V_1(P_1 - P_4) = (0.001038)(3{,}500 - 78.5)\left(\frac{1\,\text{kJ}}{1\ \text{kPa m}^3}\right) = 3.55\,\text{kJ/kg}$$

$$H_1 = H_4 + W_{p,\text{in}} = 389.6 + 3.55 = 393.15\ \text{kJ/kg}$$

Isentropic process $S_1 = S_4$ and $S_3 = S_2$.
The quality of the discharged wet steam ($S_2 < S_{3\text{sat vap}}$): $7.2297 < 7.4416$

$$x_{3'} = (7.2297 - 1.2271)/(7.4416 - 1.2271) = 0.96$$

$$H_{3'} = 389.6(1 - 0.96) + 2{,}665.0 \times 0.96 = 2{,}574.0\,\text{kJ/kg}$$

Heat interactions:
$q_{in} = H_2 - H_1 = 3{,}506.9 - 393.1 = 3{,}113.8\ \text{kJ/kg}$
$q_{out} = H_{3'} - H_4 = 2{,}574.0 - 389.6 = 2{,}184.4\ \text{kJ/kg}$

The thermodynamic efficiency of the cycle is

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = \mathbf{0.298\ or\ 29.8}\%$$

Therefore, the plant uses only 29.8% of the heat it received in the boiler.
The thermal efficiency increased from 0.276 to 0.298 by increasing the boiler temperature from 400 to 525°C. The quality of the discharged steam increased from 0.9 to 0.96, which is desirable for the protection of the turbine blades.

Turbine work out: $W_{out} = H_2 - H_{3'} = (3{,}506.9 - 2{,}574.0) = 932.9\ \text{kJ/kg}$
Cycle work out: $W_{net} = (q_{in} - q_{out}) = (3{,}113.8 - 2{,}184.4) = 929.4\ \text{kJ/kg}$

(b) $\dot{m}_s = 20.0\ \text{kg/s}$
For a 360 days of operation = (360)(24) = 8,640 h/year
The annual increase in the net power output
(20 kg/s)(929.4 – 783.1) kJ/kg (8,640) h/year = 25,280,640 kWh/year
With a unit selling price of electricity of $0.1/kWh: Annual saving = **$2,528,064**

Example 9.6 Estimation of maximum possible efficiencies in Example 9.5
Estimate the maximum possible efficiency for parts (a) and (b) in Example 9.5 and compare them with those obtained in parts (a) and (b) in Example 9.5.

Solution:
(a) The thermal efficiency of a Carnot cycle operating between the temperature limits of $T_{min} = 366.15$ K and $T_{max} = 673.15$ K:

$$\eta_{th,\,Carnot} = 1 - \frac{T_{min}}{T_{max}} = 1 - \frac{366.15\,\text{K}}{673.15\,\text{K}} = \mathbf{0.45\ or\ 45}\%$$

The ratio of the efficiencies, $\eta_{th}/\eta_{th,Carnot} = 0.276/0.45 = 0.61$ shows that only 61% of the possible efficiency is achieved in the cycle with the boiler temperature of 400°C.

(b) The thermal efficiency of a Carnot cycle operating between the temperature limits of $T_{min} = 366.15$ K and $T_{max} = 798.15$ K:

$$\eta_{th,Carnot} = 1 - \frac{T_{min}}{T_{max}} = 1 - \frac{366.15\,\text{K}}{798.15\ \text{K}} = \mathbf{0.54\ or\ 54}\%$$

The ratio of the efficiencies, $\eta_{th}/\eta_{th,Carnot} = 0.298/0.54 = 0.55$ shows that only 55% of the possible efficiency is achieved in the cycle with the boiler temperature of 525°C.

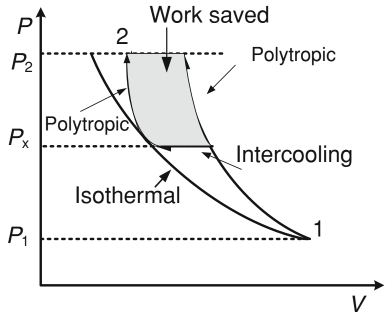


Fig. 9.2 Energy conservation in the compression work by intercooling; the work saved appears between two polytropic compressions starting at the second stage with the pressure P_x

9.2.2 Energy Conservation in the Compression and Expansion Work

It is possible to save energy in the compression work by minimizing the friction, turbulence, heat transfer, and other losses. A practical way of energy conservation is to keep the specific volume of the gas small during the compression work. This is possible by maintaining the temperature of the gas low as the specific volume is proportional to temperature. Therefore, cooling the gas as it is compressed may reduce the cost of compression work in a multistage compression with intercooling as seen in Fig. 9.2. The gas is cooled to the initial temperature between the compression stages by passing the gas through a heat exchanger called the intercooler. Energy recovery by intercooling may be significant especially when a gas is to be compressed to very high pressure [7]. Example 9.7 illustrates the energy conservation in a two-stage compression work by intercooling.

As the Fig. 9.2 shows the work saved varies with the value of intermediate pressure P_x, which needs to be optimized. The total work input for a two-stage compression process is the sum of the work inputs for each stage, and estimated by

$$W_{\text{comp}} = W_{\text{comp1}} + W_{\text{comp2}} \tag{9.4}$$

$$W_{\text{comp}} = \frac{\gamma R T_1}{MW(\gamma - 1)}\left[\left(\frac{P_x}{P_1}\right)^{(\gamma-1)/\gamma}\right] + \frac{\gamma R T_1}{MW(\gamma - 1)}\left[\left(\frac{P_2}{P_x}\right)^{(\gamma-1)/\gamma}\right]$$

In Eq. 9.4, P_x is the only variable. The optimum value of P_x is obtained by differentiation of Eq. 9.4 with respect to P_x and setting the resulting expression equal to zero. Then, the optimum value of P_x becomes

$$P_{\text{x}} = (P_1 P_2)^{1/2} \text{ or } \frac{P_x}{P_1} = \frac{P_2}{P_x} \tag{9.5}$$

Therefore, energy conservation will be maximum, when the pressure ratio across each stage of the compressor is the same and compression work at each stage becomes identical

$$W_{\text{comp1}} = W_{\text{comp2}} \tag{9.6}$$

$$W_{\text{comp}} = \frac{2\gamma RT_1}{MW(\gamma - 1)}\left[\left(\frac{P_x}{P_1}\right)^{(\gamma-1)/\gamma}\right] \tag{9.7}$$

Example 9.8 illustrates the estimation of minimum and actual power required by a compressor. Example 9.9 illustrates how to produce power out of a cryogenic expansion process. Reduction of pressure by using throttling valve wastes the energy. Replacing the throttling valve with a turbine produces power and hence conserves electricity [7].

Example 9.7 Energy conservation in a two-stage compression work by intercooling

Air with a flow rate of 2 kg/s is compressed in a steady-state and reversible process from an inlet state of 100 kPa and 300 K to an exit pressure of 1,000 kPa. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.15/kWh and the compressor is operated 360 days per year.

Solution:

Assumptions: steady-state operation; air is ideal gas; kinetic and potential energies are negligible.

$P_2 = 1{,}000$ kPa, $P_1 = 100$ kPa, $T_1 = 300$ K, $\gamma = 1.3$, $MW_{\text{air}} = 29$ kg/kmol

Basis 1 kg/s air flow rate

(a) Work needed for polytropic compression with $\gamma = 1.3$

$$W_{\text{comp}} = \frac{\gamma RT_1}{MW(\gamma - 1)}\left[\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}\right]$$

$$= \frac{1.3(8.314\,\text{kJ/kmolK})(300\,\text{K})}{29\ \text{kg/kmol}\ (1.3-1)}\left[\left(\frac{1{,}000}{300}\right)^{(1.3-1)/1.3} - 1\right] = \mathbf{261.3\,kJ/kg}$$

(b) Ideal two-stage polytropic compression with intercooling ($\gamma = 1.3$)

$$P_x = (P_1P_2)^{1/2} = (100 \times 1{,}000)^{1/2} = 316.2\,\text{kPa}$$

$$W_{\text{comp}} = \frac{2\gamma RT_1}{MW(\gamma - 1)}\left[\left(\frac{P_x}{P_1}\right)^{(\gamma-1)/\gamma}\right]$$

$$= \frac{2(1.3)(8.314\,\text{kJ/kmolK})(300\,\text{K})}{29\ \text{kg/kmol}\ (1.3-1)}\left[\left(\frac{316.2}{100}\right)^{(1.3-1)/1.3} - 1\right] = \mathbf{226.8\,kJ/kg}$$

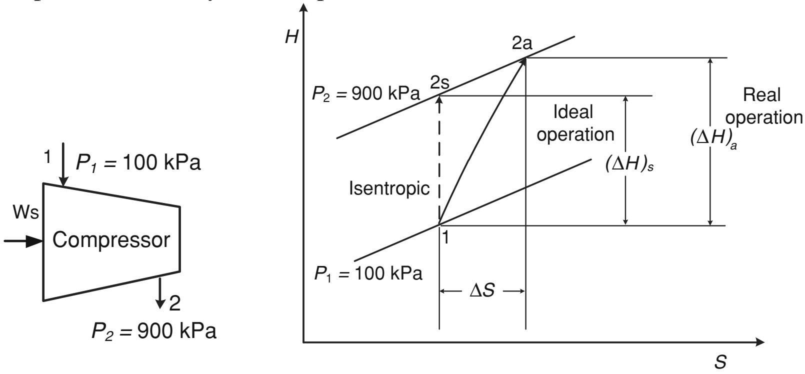
Recovered energy = (261.3 – 226.8) kJ/kg = 34.5 kJ/kg

Reduction in energy use: $\dfrac{261.3 - 226.8}{261.3} = 0.13$ or 13%

(c) Conservation of compression work = (2 kg/s) (261.3 – 226.8) kJ/kg = 69 kW
Yearly conserved work: (69 kW) (8,640 h/year) = 596,160 kWh/year
Saving in electricity (2,385,745 kWh/year) ($0.15/kWh) = **$89,424/year**

The compression work has been reduced by 13% when two stages of polytropic compression are used instead of single polytropic compression and conserved 596,160 kWh/year.

Example 9.8 Compressor efficiency and power input
An adiabatic compressor is used to compress air from 100 kPa and 290 K to a pressure of 900 kPa at a steady-state operation. The isentropic efficiency of the compressor is 80%. The air flow rate is 0.4 kg/s. Determine the minimum and actual power needed by the compressor.



Solution:
Assume: steady-state adiabatic operation. Air is ideal gas. The changes in kinetic and potential energies are negligible.

Enthalpies of ideal gas depend on temperature only.
The air mass flow rate = 0.4 kg/s, $\eta_C = 0.8$
Inlet conditions (Table D1):

$P_1 = 100$ kPa, $T_1 = 290$ K, $H_1 = 290.16$ kJ/kg, $Pr_1 = 1.2311$

Exit conditions (Table D1): $P_2 = 900$ kPa
Enthalpy of air at the exit is from Eq. 7.36 and Table D1.

$$Pr_2 = Pr_1 \frac{P_2}{P_1} = 1.2311 \left(\frac{900\,\text{kPa}}{100\ \text{kPa}} \right) = 11.1$$

From Table D1: for $Pr_2 = 11.1$, we find $T_2 = 540$ K and $H_{2s} = 544.35$ kJ/kg

$$\eta_C = \frac{H_{2s} - H_1}{H_{2a} - H_1} = 0.8 \rightarrow H_{2a}$$

$H_{2a} = 607.9$ kJ/kg and $T_2 = 600$ K (Table D1) (Approximate)
As seen from the *TS* diagram above H_{2a} is the actual enthalpy at the exit.

Actual power required:

$\dot{m}\Delta H_a = \dot{W}_{\text{net, in}} = \dot{m}(H_{2a} - H_1) = 0.4\ \text{kg/s}\ (607.9 - 290.16)\ \text{kJ/kg} = \mathbf{127.1\,kW}$

Minimum power required:

$\dot{m}\Delta H_s = \dot{W}_{\text{net, in}} = \dot{m}(H_{2s} - H_1) = 0.4\ \text{kg/s}\ (544.3 - 290.1)\ \text{kJ/kg} = \mathbf{101.7\,kW}$

If the operation was ideal the rate of conserved energy would be 25.4 kW or 20% savings.

Example 9.9 Energy conservation in expansion by replacing a throttle valve with a turbine

A cryogenic manufacturing plant handles liquid methane at 115 K and 5,000 kPa at a rate of 0.3 m^3/s. In the plant a throttling valve reduces the pressure of liquid methane to 1,000 kPa. A new process considered replaces the throttling valve with a turbine in order to produce power while reducing the pressure to 1,000 kPa at 110 K. Using the data for the properties of liquid methane below estimate:

(a) the power that can be produced by the turbine.
(b) the savings in electricity usage per year if the turbine operates 360 days per year with a unit cost of electricity at $0.09/kWh.

T (K)	P (kPa)	H (kJ/kg)	S (kJ/kg K)	C_p (kJ/kg K)	ρ (kg/m^3)
110	1,000	209.0	4.875	3.471	425.8
110	2,000	210.5	4.867	3.460	426.6
110	5,000	215.0	4.844	3.432	429.1
120	1,000	244.1	5.180	3.543	411.0
120	2,000	245.4	5.171	3.528	412.0
120	5,000	249.6	5.145	3.486	415.2

Source Çengel and Turner [7]

Solution:

Assumptions: steady-state and reversible operation; adiabatic turbine, methane is ideal gas; kinetic and potential energies are negligible.

(a) $P_1 = 5{,}000$ kPa, $T_1 = 115$ K, $Q_1 = 0.30$ m^3/s
$H_1 = 232.3$ kJ/kg $= (215.0 + 249.6)/2$, $\rho_1 = 422.15$ kg/m^3 $= (429.1 + 415.2)/2$
$P_2 = 1{,}000$ kPa, $H_2 = 209.0$ kJ/kg
Unit cost of electricity = $0.09/kWh
Mass flow rate: $\dot{m} = \rho Q_1 = 422.15\ \text{kg/m}^3 (0.3\ \text{m}^3/\text{s}) = 126.6\ \text{kg/s}$

Power produced:

$\dot{W}_{\text{out}} = \dot{m}(H_1 - H_2) = 126.6\ \text{kg/s}\ (232.5 - 209.0)\text{kJ/kg} = \mathbf{2{,}949.8\,kW}$

Annual power production:

$\dot{W}_{\text{out}}\Delta t = (2{,}949.8\,\text{kW})(360)(24)\text{h/year} = 25{,}486{,}099\ \text{kW h/year}$

Saving in electricity usage:
(25,486,099 kWh/year)($0.09/kWh) = **$2,293,748/year**

Reduction of pressure by using throttling valve wastes the potential of power production. Replacing the valve with a turbine will produce power and hence conserve electricity.

9.2.3 Conservation of Energy by High-Efficiency Electric Motors

Practically all compressors are powered by electric motor. Electric motors cannot convert the electrical energy they consume into mechanical energy completely. Electric motor efficiency is defined by

$$\eta_{\mathrm{Motor}} = \frac{\text{mechanical power}}{\text{electrical power}} = \frac{\dot{W}_{\mathrm{comp}}}{\dot{W}_{\mathrm{elect}}} \tag{9.8}$$

Motor efficiency range: $0.7 < \eta_{\mathrm{motor}} < 96$. The portion of electric energy that is not converted to mechanical power is converted to heat, which is mostly unusable.

For example, assuming that no transmission losses occur:

- A motor with an efficiency of 80% will draw an electrical power of 1/0.8 = 1.25 kW for each kW of shaft power it delivers.
- If the motor is 95% efficient, then it will draw 1/0.95 = 1.05 kW only to deliver 1 kW of shaft work.
- Therefore between these two motors, electric power conservation is 1.25 (η_{motor} = 95%) kW – 1.05 (η_{motor} = 95%) = 0.20 kW.

High-efficiency motors are more expensive but its operation saves energy. Saved energy is estimated by

$$\dot{W}_{\mathrm{elect.saved}} = \dot{W}_{\mathrm{elect.std}} - \dot{W}_{\mathrm{elect.efficient}} = \dot{W}_{\mathrm{comp}}\left(\frac{1}{\eta_{\mathrm{std}}} - \frac{1}{\eta_{\mathrm{efficient}}}\right) \tag{9.9}$$

$$\dot{W}_{\mathrm{elect.saved}} = (\text{Rated power})(\text{Load factor})\left(\frac{1}{\eta_{\mathrm{std}}} - \frac{1}{\eta_{\mathrm{efficient}}}\right) \tag{9.10}$$

where the *rated power* is the nominal power delivered at full load of the motor and listed on its label. *Load factor* is the fraction of the rated power at which the motor normally operates. Annual saving is estimated by

$$\text{Annual energy saving} = (\dot{W}_{\mathrm{elect.saved}})(\text{Annual operation hours}) \tag{9.11}$$

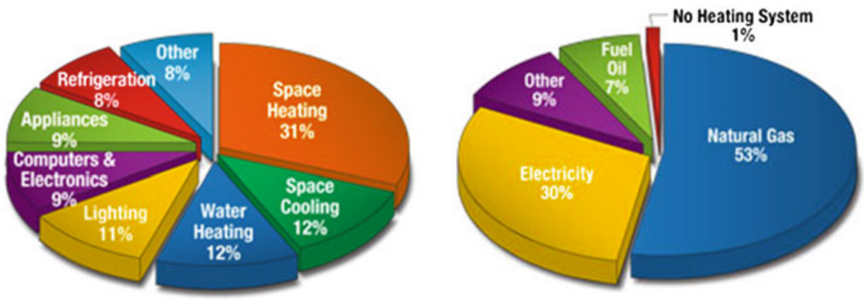


Fig. 9.3 **a** Home usage of energy: Heating is the largest part of the energy cost. Heating and cooling consume more energy than any other system at home. Typically, 50% of the utility bill goes for heating and cooling, **b** Household heating by various sources; use of natural gas has the largest source of fuel for heating houses

- A compressor that operates at partial load causes the motor to operate less efficiently. The efficiency of motor will increase with the load.
- Using the cold outside air for compressor intake lowers the compressor work and conserves energy.

9.3 Energy Conservation in Home Heating and Cooling

Space heating and cooling as well as water heating at home accounts around 55% of the utility bill as seen in Fig. 9.3a. To conserve energy, one should identify from where the home is losing energy, assign priorities, and form an efficiency plan that improves efficiency and reduces costs. For example, the potential energy savings from reducing drafts in a home may range from 5 to 30% per year. Heat loss through the ceiling and walls in your home could be very large if the insulation levels are less than the recommended minimum. Inspect heating and cooling equipment annually, or as recommended by the manufacturer. If the unit is more than 15 years old, the newer and energy-efficient units may reduce the cost [1, 2, 20]. Sources for heating vary as seen in Fig. 9.3b. Use of natural gas has the largest source of fuel for heating houses in the United States. In colder climates, windows that are gas filled with low emissivity coatings on the glass reduces heat loss. In warmer climates, windows with selective coatings may reduce heat gain (see Fig. 9.4). Setting the thermostat low in the winter and high in the summer as comfortable as possible may reduce the cost of heating and cooling. Also the followings can reduce the cost:

- Clean or replace filters on furnaces once a month or as needed.
- Clean baseboard heaters and radiators and make sure they are not blocked.

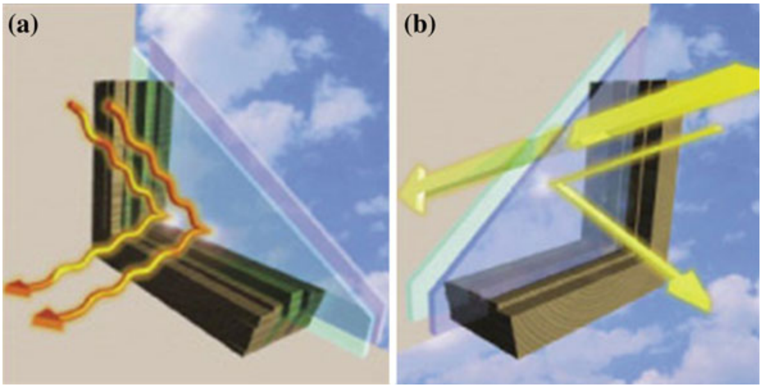


Fig. 9.4 **a** Double-pane windows with low-emittance coating on the glass reflect heat back into the room during the winter months, **b** Windows with low-emittance coatings on the glass reflect some of the sunlight, keeping your rooms cooler [26]

- During summer, keep the window coverings closed during the day to lower solar gain.
- Select energy-efficient products when you buy new heating and cooling equipment.

Water heating typically accounts for about 12% of your utility bill. Insulate the electric, natural gas, or oil hot-water storage tank as shown in Fig. 9.5. Most water heaters can last around 15 years. However replacing the units older than 7 years may reduce the cost of energy.

9.3.1 Home Heating by Fossil Fuels

Residential furnaces have a heat input rate of less than 225,000 Btu/h (66,000 W) and residential boilers have a heat input rate of less than 300,000 Btu/h (88,000 W). The residential furnace is an appliance that provides heated air with a blower to circulate air through the duct distribution system. The residential boiler is a cast-iron, steel, aluminum, or copper pressure vessel heat exchanger designed to burn fossil fuels to heat a suitable medium such as water. Hot water can be distributed via baseboard radiators or radiant floor systems, while steam is distributed through pipes to steam radiators. Furnaces heat air and distribute the heated air through the house using ducts, while boilers heat water, providing either hot water or steam for heating. Most furnaces and boilers operate on natural gas, oil, or propane. Steam boilers operate at a higher temperature than hot-water boilers. Oil-fired furnaces and boilers can use heating oil blended with biodiesel, which produce less pollution than pure heating oil [20, 23].

A condensing furnace or boiler condenses the water vapor produced in the combustion process and uses the heat from this condensation. Although

Fig. 9.5 Water heater

condensing units cost more than non-condensing units, the condensing unit can reduce the consumption of fuel and the cost over the 15-to 20-year life of the unit. Old furnaces and boilers can be retrofitted to increase their efficiency. Some retrofitting options include installing programmable thermostats, upgrading ductwork in forced-air systems, and adding zone control for hot-water systems. Still the costs of retrofits should be compared with the cost of a new boiler or furnace.

9.3.2 Home Heating by Electric Resistance

An all-electric furnace or boiler has no flue loss through a chimney. Electric resistance heating converts nearly 100% of the energy in the electricity to heat. However, most electricity is produced from oil, natural gas, or coal by converting only about 30% of the fuel's energy into electricity. Because of production and transmission losses, electric heat is often more expensive than heat produced using combustion appliances, such as natural gas, propane, and oil furnaces. Heat pumps are preferable in most climates, as they easily cut electricity use by 50% when compared with electric resistance heating. It is also possible to use heat storage systems to avoid heating during times of peak power demand [3].

Blowers (large fans) in electric furnaces move air over a group of three to seven electric resistance coils, called elements, each of which is typically rated at 5 kW. A built-in thermostat prevents overheating and may shut the furnace off if the blower fails or if a dirty filter blocks the airflow.

When operated in heating mode, a heat pump is more efficient than operating resistance heaters. Because an electric heater can convert only the input electrical energy directly to output heat energy with none of the efficiency or conversion advantages of a heat pump. Likewise, when a heat pump operates near its most inefficient outside temperature, typically 0°F, the heat pump will perform close to the same as a resistance heater. Example 9.10 illustrates a simple analysis of heating a house by heat pump. Example 9.11 discusses the energy conservation in house heating by Carnot heat pump.

Fig. 9.6 A home using a liquid-based solar system for space and water heating. The solar units are environmentally friendly and can be installed on roof to blend with the architecture of a house [18, 26]

9.3.3 Home Heating by Solar Systems

Active or passive solar systems can be used for residential heating. There are two basic types of active solar heating systems using either liquid or air heated in the solar collectors. The solar units are environmentally friendly and can now be installed on an a roof to blend with the architecture of a house. *Liquid-based systems*, as shown in Fig. 9.6, heat water or an antifreeze solution, whereas *air-based systems* heat air in an air collector [10]. A circulating pump transports the fluid through the collector so its temperature increases 10–20°F (5.6–11°C). The flow rate through a solar-water collector should be between 0.02 and 0.03 gallons per minute per square foot of collector. Both of these systems absorb solar radiation and transfer it directly to the interior space or to a storage system. Liquid systems are more often used when storage is included, and are well suited for boilers with hot-water radiators and heat pumps. These collectors easily last decades.

Active solar heating systems may reduce the cost more when they are used for most of the year. The economics of an active space heating system improve if it also heats domestic water. Heating homes with active solar energy systems can significantly reduce the fossil fuel consumptions, air pollution, and emission of greenhouse gases [19].

Passive solar heaters do not have fans or blowers. In passive solar building design, windows, walls, and floors are made to collect, store, and distribute solar energy in the form of heat in the winter and reject solar heat in the summer. A passive solar building takes advantage of the local climate. Elements to be considered include window placement, thermal insulation, thermal mass, and shading.

Example 9.10 Heating a house by heat pump
A heat pump is used to heat a house and maintain it at 18°C. On a day where the outside temperature is −2°C, the house is losing heat at a rate of 75,000 kJ/h. The heat pump operates with a coefficient of performance (COP) of 2.8. Determine (a) power needed by the heat pump, (b) the rate of heat absorbed from the surrounding cold air.

Solution:
Assume: steady-state operation.

(a) House is maintained at 18°C.
Heat pump must supply the same amount of lost heat from the cold source:
q_H = 75,000 kJ/h = 20.83 kW
Power required by the heat pump:

$$\mathrm{COP_{HP}} = \frac{\dot{q}_H}{\dot{W}_{\mathrm{net,in}}} \rightarrow \dot{W}_{\mathrm{net,in}} = \frac{\dot{q}_H}{\mathrm{COP_{HP}}} = \frac{20.83\,\mathrm{kW}}{2.8} = \mathbf{7.44\,kW}$$

(b) Energy balance: $\dot{q}_H - \dot{q}_C = \dot{W}_{\mathrm{net,in}} = 7.44\ \mathrm{kW}$
$\dot{q}_C = \dot{q}_H - \dot{W}_{\mathrm{net,in}} = (20.83 - 7.44)\mathrm{kW} = \mathbf{13.39\,kW}$
13.39 kW is extracted from the outside. The house is paying only for the energy of 7.44 kW that is supplied as electrical work to the heat pump.
If we have to use electricity in a resistance heater we have to supply 20.83 kW, so the energy conserved by using heat pump instead of electric heater is 13.39/20.83 = 0.64 (or 64%).

Example 9.11 Energy conservation in house heating by Carnot heat pump
A Carnot heat pump is used to heat a house during the winter. The house is maintained at 20°C. The house is estimated to be losing heat at a rate of 120,000 kJ/h when the outside temperature is −4°C. Determine the minimum power needed by the heat pump and the rate of heat absorbed from the surrounding cold air.

Solution:
Assume: Steady-state operation.

The temperatures of hot and cold sources:
$T_H = 273.15 + 20°\mathrm{C} = 293.15$ K and $T_C = 273.15 - 4°\mathrm{C} = 269.15$ K
The amount of heat to be supplied to warm inside room:
$q_H = 120{,}000$ kJ/h = 33.33 kW
Minimum amount of power is possible only for a fully reversible heat pump. This heat pump is Carnot heat pump.
Coefficient of performance for a Carnot heat pump:

$$\mathrm{COP_{HP}} = \frac{\dot{q}_H}{\dot{W}_{\mathrm{net,in}}} = \frac{1}{1-(T_C/T_H)} = \frac{1}{1-(269.15\,\mathrm{K}/293.15\,\mathrm{K})} = 12.2$$

Since the house is losing heat at a rate of 120,000 kJ/h to maintain the house 20°C, the heat pump must supply the same amount of heat from the cold source:

Energy balance: $\mathrm{COP_{HP}} = \dfrac{\dot{q}_H}{\dot{W}_{\mathrm{net,in}}} \rightarrow \dot{W}_{\mathrm{net,in}} = \dfrac{\dot{q}_H}{\mathrm{COP_{HP}}} = \mathbf{2.73\,kW}$

Table 9.1 Some typical values of annual fuel utilization efficiency (AFUE) for furnace and boilers

Fuel	Furnace/boiler	AFUE (%)
Heating oil	Cast-iron (pre-1970)	60
	Retention head burner	70–78
	Mid-efficiency	83–89
Electric heating	Central or baseboard	100
Natural gas	Conventional	55–65
	Mid-efficiency	78–84
	Condensing	90–97
Propane	Conventional	55–65
	Mid-efficiency	79–85
	Condensing	88–95
Firewood	Conventional	45–55
	Advanced	55–65
	State-of-the-Art	75–90

Lekov et al. [21]

$$\dot{q}_C = \dot{q}_H - \dot{W}_{\text{net, in}} = (33.3 - 2.73)\text{kW} = \mathbf{30.57\,kW}$$

The house pays for only 2.73 kW. If we use electricity for heating by an electric resistance heater, the rate of heat necessary is 33.3 kW. A necessary heat of 30.6 kW is supplied from the surrounding cold air. Therefore, the energy conserved is 30.6/33.3 = 0.92 (or 92%).

9.4 Energy Efficiency Standards

Thermal efficiency of residential furnaces and boilers is measured by annual fuel utilization efficiency (AFUE). Annual fuel utilization efficiency is the ratio of heat output of the furnace or boiler compared to the total energy consumed by them over a typical year. Annual fuel utilization efficiency does not account for the circulating air and combustion fan power consumptions and the heat losses of the distributing systems of duct or piping. An AFUE of 90% means that 90% of the energy in the fuel becomes heat for the home and the other 10% escapes up the chimney and elsewhere. Heat losses of the duct system or piping can be as much as 35% of the energy output of the furnace. Table 9.1 shows some typical values of AFUE for furnace and boiler using various fossil fuels and electricity [21]. Some of the minimum allowed AFUE ratings in the United States are:

- Non-condensing fossil-fueled, warm-air furnace is 78%.
- Fossil-fueled boiler is 80%.
- Gas-fueled steam boiler is 75%.

The annual savings from replacement of heating system with more efficient one may be estimated by using Table 9.2 assuming that both systems have the same

Table 9.2 Assuming the same heat output, estimated savings for every $100 of fuel costs by increasing an existing heating equipment efficiency

Existing System AFUE (%)	New and upgraded system AFUE (%)							
	60	65	70	75	80	85	90	95
55	$8.3	$15.4	$21.4	$26.7	$31.2	$35.3	$38.9	$42.1
60	–	$7.7	$14.3	$20.0	$25.0	$29.4	$33.3	$37.8
65	–	–	$7.1	$13.3	$18.8	$23.5	$27.8	$31.6
70	–	–	–	$6.7	$12.5	$17.6	$22.2	$26.3
75	–	–	–	–	$6.5	$11.8	$16.7	$21.1
80	–	–	–	–	–	$5.9	$11.1	$15.8
85	–	–	–	–	–	–	$5.6	$10.5

Lekov et al. [21]

heat output. For older units, actual savings in upgrading to a new system could be much higher than that indicated in the table.

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) is an international technical society for heating, ventilation, air-conditioning, and refrigeration. AFUE is calculated using ASHRAE Standard 103 (ASHRAE 2007). A furnace with a thermal efficiency of 78% may yield an AFUE of only 64% or so, for example, under the standards' test conditions.

9.4.1 Efficiency of Air Conditioner

The Energy Efficiency Ratio (EER) of a particular cooling device is the ratio of *output* cooling (in Btu/h) to *input* electrical power (in Watts) at a given operating point. The efficiency of air conditioners is often rated by the *Seasonal Energy Efficiency Ratio* (SEER). The SEER rating of a unit is the cooling output in Btu during a typical cooling season divided by the total electric energy input in watt-hours during the same period. The coefficient of performance (COP) is an instantaneous measure (i.e. a measure of power divided by power), whereas both EER and SEER are averaged over a duration of time. The time duration considered is several hours of constant conditions for EER, and a full year of typical meteorological and indoor conditions for SEER. Typical EER for residential central cooling units $= 0.875 \times$ SEER. A SEER of 13 is approximately equivalent to a COP of 3.43, which means that 3.43 units of heat energy are removed from indoors per unit of work energy used to run the heat pump. SEER rating more accurately reflects overall system efficiency on a seasonal basis and EER reflects the system's energy efficiency at peak day operations.

Air conditioner sizes are often given as "tons" of cooling where 1 ton of cooling is being equivalent to 12,000 Btu/h (3,500 W). This is approximately the power required to melt one ton of ice in 24 h. Example 9.12 illustrates the estimation of electric cost of an air conditioner.

Example 9.12 Electricity cost of air conditioner
Estimate the cost of electricity for a 5,000 Btu/h (1,500 W) air-conditioning unit operating, with a SEER of 10 Btu/W h. The unit is used for a total of 1,500 h during an annual cooling season and the unit cost of electricity is $0.14/kWh.

Solution:
Air conditioner sizes are often given as "tons" of cooling where 1 ton of cooling is being equivalent to 12,000 Btu/h (3,500 W).
The unit considered is a small unit and the annual total cooling output would be:
(5,000 Btu/h) × (1,500 h/year) = 7,500,000 Btu/year
With a seasonal energy efficiency ratio (SEER) of 10, the annual electrical energy usage:
(7,500,000 Btu/year)/(10 Btu/Wh) = 750,000 Wh/year = 750 kW h/year
With a unit cost of electricity of $0.14/kWh, the annual cost:
(750 kWh/year)($0.14/kWh) = **$105/year**
The average power usage may also be calculated more simply by:
Average power = (Btu/hr)/(SEER, Btu/Wh) = 5,000/10 = 500 W = 0.5 kW
With the electricity cost of $0.14/kWh, the cost per hour:
(0.5 kW) ($0.14)/kWh = $0.07/h
For 1,500 h/year, the total cost: ($0.07/h) (1,500 h/year) **= $105**

9.4.2 Maximum Possible Efficiency for Cooling

The refrigeration process with the maximum possible efficiency is the Carnot cycle. The coefficient of performance (COP) of an air conditioner using the Carnot cycle is:

$$\mathrm{COP}_{\mathrm{Carnot}} = \frac{T_C}{T_H - T_C} \tag{9.12}$$

where T_C is the indoor temperature and T_H is the outdoor temperature in K or R. The EER is calculated by multiplying the COP by 3.413 which is the conversion factor from Btu/h to Watts:

$$\mathrm{EER}_{\mathrm{Carnot}} = 3.413(\mathrm{COP}_{\mathrm{Carnot}}) \tag{9.13}$$

For an outdoor temperature of 100°F (311 K) and an indoor temperature of 95°F (308 K), the above equation gives a COP of 103, or an EER of 350. This is about 10 times as efficient as a typical home air conditioner available today. The maximum EER decreases as the difference between the inside and outside air temperature increases. For example:

T_H = 120 F (49°C) = 322.15 K, and T_C = 80°F (27°C) = 300.15 K

$\mathrm{COP}_{\mathrm{Carnot}}$ = 300.15 K/(322.15 – 300.15) K = 13.6 or
EER = (3.413) (13.6) = 46.4

The maximum SEER can be calculated by averaging the maximum values of EER over the range of expected temperatures for the season.

Central air conditioners should have a SEER of at least 14. Substantial energy savings can be obtained from more efficient systems. For example:

By upgrading from SEER 9 to SEER 13.
Reduction in power consumption = (1 − 9/13) = 0.30.

This means that the power consumption is reduced by 30%. Residential air condition units may be available with SEER ratings up to 26. Example 9.13 illustrates the calculation of the annual cost of power used by an air conditioner. Example 9.14 discusses possible saving in cooling by using a unit operating at a higher SEER rating.

Example 9.13 Calculating the annual cost of power for an air conditioner
Estimate the annual cost of electric power consumed by a 6 ton air conditioning unit operating for 2,000 h per year with a SEER rating of 10 and a power cost of $0.16/kWh.

Solution:
Air conditioner sizes are often given as "tons" of cooling:
1 ton of cooling = 12,000 Btu/h (3,500 W).
This is approximately the power required to melt one ton of ice in 24 h.
The annual cost of electric power consumption: (6)(12,000 Btu/h) = 72,000 Btu/h

$$\text{Cost} = \frac{(\text{Size, Btu/h})(\text{time, h/year})(\text{Cost of energy, \$/kWh})}{(\text{SEER, Btu/Wh})(1{,}000\ \text{W/kW})}$$

(72,000 Btu/h)(2,000 h/year)($0.16/kWh)/[(10 Btu/W h)(1,000 W/kW)]
= **$2,304/ year**
For the temperatures of hot and cold sources:
$T_H = 273.15 + 20°\text{C} = 293.15$ K
$T_C = 273.15 - 4°\text{C} = 269.15$ K
$T_H - T_C = 24$ K

$$\text{EER}_{\text{Carnot}} = 3.41\left(\frac{T_C}{T_H - T_C}\right) = 3.41(269.13/24) = \mathbf{38.24}$$

The maximum EER decreases as the difference between the inside and outside air temperature increases.

Example 9.14 Reducing the cost of cooling with a unit operating at a higher SEER rating
A 4 ton current residential air conditioner operates with a seasonal energy efficiency ratio (SEER) rating of 10. This unit will be replaced with a newer unit operating with a SEER rating of 22. The unit operates 130 days with an average 10 h per day. Average inside and outside temperatures are 21 and 3°C, respectively. The unit cost of energy is $0.16/kWh. Estimate the savings in the cost of electricity and the maximum energy efficiency ratio.

Solution:
Cooling load of 4 tons: (4)(12,000 Btu/h) = 48,000 Btu/h (14,000 W).
(130 days/year)(10 h/day) = 1,300 h/year
The estimated cost of electrical power:
SEER = 10, and an energy cost of \$0.16/kWh, using 130 days of 10 h/day operation:
Cost = (48,000 Btu/h)(1,300 h/year)(\$0.16/kWh)/[(10 Btu/W h)(1,000 W/kW)]
= \$998.4/year
SEER = 22, and an energy cost of \$0.16/kWh, using 130 days of 10 h/day operation:
Cost = (48,000 Btu/h)(1,300 h/year)(\$0.16/kWh)/[(22 Btu/W h)(1,000 W/kW)]
= \$453.8/year
Annual saving = \$998.4/year − \$453.8/year = **\$44.6/year**
The ratio of typical EER to maximum $EER/EER_{max} = 19.25/52.31 = 0.368$

Typical EER for the current cooling unit:
EER = 0.875 (SEER) = 0.875 (10) = 8.75

Typical EER for the new cooling unit:
EER = 0.875 (SEER) = 0.875 (22) = 19.25

Maximum value of EER:
The temperatures of hot and cold sources:
$T_H = 273.15 + 21°C = 294.15$ K
$T_C = 273.15 + 3°C = 276.15$ K
$T_H - T_C = 18$ K

$$EER_{Carnot} = 3.41\left(\frac{T_C}{T_H - T_C}\right) = 3.41(276.13/18) = \mathbf{52.31}$$

The maximum EER decreases as the difference between the inside and outside air temperature increases. The annual saving is significant after using a more efficient unit. The value of EER for the new unit is only 36.6% of the maximum value of EER.

9.4.3 Fuel Efficiency

Fuel efficiency means the efficiency of a process that converts chemical energy contained in a fuel into kinetic energy or work. The increased fuel efficiency is especially beneficial for fossil fuel power plants or industries dealing with combustion of fuels. In the transportation field, fuel efficiency is expressed in miles per gallon (mpg) or kilometers per liter (km/l). Fuel efficiency is dependent on many parameters of a vehicle, including its engine parameters, aerodynamic drag, and weight. Hybrid vehicles offer higher fuel efficiency using two or more power sources for propulsion, such as a small combustion engine combined with and electric motors [21, 16, 11]. Example 9.15 compares the heating by electricity and by natural gas. Examples 9.16 and 9.17 discuss the amounts of coal necessary in a coal-fired steam power plant in two different efficiency values for the combustion and generator efficiency. The examples show that with the increased combustion

efficiency and generator efficiency, the required amount of coal is reduced to 23.9 from 36.6 ton/h. This leads to around 35% savings of coal.

Example 9.15 Comparison of energy sources of electricity with natural gas for heating

The efficiency of electric heater is around 73%, while it is 38% for natural gas heaters. A house heating requires 4 kW. The unit cost of electricity is \$0.1/kWh, while the natural gas costs \$0.60/therm. Estimate the rate of energy consumptions for both the electric and gas heating systems.

Solution:

Energy supplied by the electric heater:

$q_{\text{used}} = q_{\text{in}}\,\eta_{\text{th}} = (4\text{ kW})\,(0.73) = 2.92\text{ kW}$

The unit cost of energy is inversely proportional to the efficiency:

Unit cost of electric energy = (unit cost of energy)/(efficiency)

= \$0.1/0.73 = **\$0.137/kWh**

Therm = 29.3 kWh (Table 1.10)

Energy input to the gas heater (at the same rate of used energy that is 2.92 kW):

$q_{\text{in, gas}} = q_{\text{used}}/\eta_{\text{th}} = 2.92/0.38 = 3.84\text{ kW}$ (=13100 Btu/h)

Therefore, a gas burner should have a rating of at least 13,100 Btu/h to have the same performance as the electric unit.

Unit cost of energy from the gas = cost of energy/efficiency

= [(\$0.60/therm)/(29.3 kWh/therm)]/0.38

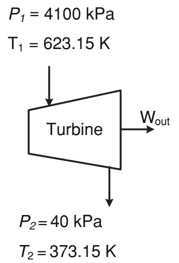
= **\$0.054/kWh**

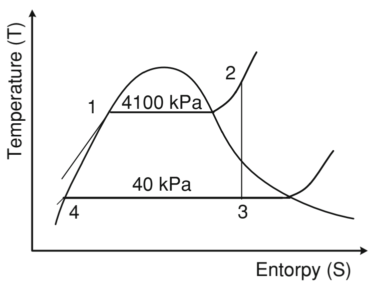
Ratio of unit cost of gas to electric energy; \$0.054/\$0.137 = 0.39

The cost of utilized natural gas is around 39% of the electricity cost; therefore heating with an electric heater will cost more for heating.

Example 9.16 Overall plant efficiency and required amount of coal in a coal-fired steam power plant

An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The power output is 50 MW. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.75 and the generator efficiency is 0.9, determine the overall plant efficiency and the amount of coal supplied per hour.





Solution:
Assume: steady-state adiabatic operation. The changes in kinetic and potential energies are negligible.

Basis: steam flow rate = 1 kg/s
Combustion efficiency $\eta_{comb} = 0.75$
Generator efficiency $\eta_{gen} = 0.9$
Power output = 50 MW = 50,000 kW
From Table F4:
Turbine inlet conditions:
$P_2 = 4{,}100$ kPa, $T_2 = 623.15$ K, $H_2 = 3{,}092.8$ kJ/kg, $S_2 = 6.5727$ kJ/kg K
Turbine outlet conditions:
$P_4 = P_3 = 40$ kPa, $T_3 = 373.15$ K, $V_4 = 1.027$ cm^3/g $= 0.001027$ m^3/kg
$S_{4\text{sat vap}} = 7.6709$ kJ/kg K, $S_{4\text{sat liq}} = 1.2026$ kJ/kg K at 40 kPa
$H_{4\text{sat vap}} = 2{,}636.9$ kJ/kg, $H_{4\text{sat liq}} = 317.6$ kJ/kg at 40 kPa (Table F3)

$$W_{p,\text{in}} = V_4(P_1 - P_4) = (0.001027\ \text{m}^3/\text{kg})\,(4{,}100 - 40)\text{kPa}\left(1\ \text{kJ}/1\,\text{kPa m}^3\right) = 4.2\ \text{kJ/kg}$$
$$H_1 = H_4 + W_{p,\text{in}} = 317.6 + 4.2 = 321.8\ \text{kJ/kg}$$

For the isentropic operation $S_3 = S_2 = 6.5727$ kJ/kg K
Since $S_2 < S_{3\text{sat vap}}$: $6.5727 < 7.6709$ the steam at the exit is saturated liquid–vapor mixture.

Quality of that mixture: $x_3 = \dfrac{S_2 - S_{2\text{sat liq}}}{S_{2\text{sat vap}} - S_{2\text{sat liq}}} = \dfrac{6.5727 - 1.2026}{7.6709 - 1.2026} = 0.83$

$$H_3 = (1 - x_3)H_{3\text{sat liq}} + x_3 H_{3\text{sat vap}} = 2243.1\ \text{kJ/kg}$$

Heat interactions:
$$q_{\text{in}} = \dot{m}(H_2 - H_1) = (3{,}092.8 - 321.8)\ \text{kJ/kg} = 2771.0\ \text{kJ/s}$$
$$q_{\text{out}} = \dot{m}(H_3 - H_4) = (2{,}243.1 - 317.6)\ \text{kJ/kg} = 1{,}925.5\ \text{kJ/s}$$

Thermal efficiency: $\eta_{th} = 1 - \dfrac{q_{out}}{q_{in}} = 0.305$ or 30.5%

Overall plant efficiency: $\eta_{overall} = \eta_{th}\eta_{comb}\eta_{gen}$ = (0.305)(0.75)(0.9) = **0.205 or 20.5%**

The rate of coal energy required: $\dot{E}_{coal} = \dfrac{\dot{W}_{net}}{\eta_{overall}} = \dfrac{50{,}000\ \text{kW}}{0.205}$ = 243,900 kJ/s

Energy of coal (bituminous) = 24,000 kJ/kg (Table 2.6)

$$\dot{m}_{coal} = \frac{\dot{E}_{coal}}{\eta_{overall}} = \frac{243{,}900}{24{,}000}\left(\frac{1\ \text{ton}}{1{,}000\ \text{kg}}\right) = 0.0101\ \text{ton/s} = \mathbf{36.6\ ton/h}$$

Example 9.17 Required amount of coal in a coal-fired steam power plant
An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The steam flow rate is 42 kg/s. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.77 and the generator efficiency is 0.95, determine the overall plant efficiency and the amount of coal supplied per hour.

Solution:
Assume: steady-state adiabatic operation. The changes in kinetic and potential energies are negligible.

Basis: steam flow rate = 1 kg/s
Combustion efficiency $\eta_{comb} = 0.77$
Generator efficiency $\eta_{gen} = 0.95$

Turbine inlet:
$P_2 = 4{,}100$ kPa, $T_2 = 623.15$ K, $H_2 = 3{,}092.8$ kJ/kg, $S_2 = 6.5727$ kJ/kg K (Table F4)

Turbine exit:
$P_4 = P_3 = 40$ kPa $T_3 = 373.15$ K, $V_4 = 1.027$ cm^3/g = 0.001027 m^3/kg (Table F3)
$S_{4\text{sat vap}} = 7.6709$ kJ/kg K, $S_{4\text{sat liq}} = 1.2026$ kJ/kg K at 40 kPa
$H_{4\text{sat vap}} = 2{,}636.9$ kJ/kg, $H_{4\text{sat liq}} = 317.6$ kJ/kg at 40 kPa (Table F4)

$W_{p,\text{in}} = V_4(P_1 - P_4) = (0.001027 \text{ m3/kg})(4{,}100 - 40) \text{ kPa } (1 \text{ kJ}/1 \text{ kPa m}^3)$
$= 4.2$ kJ/kg
$H_1 = H_4 + W_{p,\text{in}} = 317.6 + 4.2 = 321.8$ kJ/kg
For the isentropic operation $S_3 = S_2 = 6.5727$ kJ/kg K
Since $S_2 < S_{3\text{sat vap}}$: $6.5727 < 7.6709$ the steam at the exit is saturated liquid–vapor mixture.
Quality of the mixture: $x_3 = \dfrac{S_2 - S_{2\text{sat liq}}}{S_{2\text{sat vap}} - S_{2\text{sat liq}}} = \dfrac{6.5727 - 1.2026}{7.6709 - 1.2026} = 0.83$
$H_3 = (1 - x_3)H_{3\text{sat liq}} + x_3 H_{3\text{sat vap}} = 2{,}243.1 \text{ kJ/kg}$

Heat interactions:
$q_{\text{in}} = (H_2 - H_1) = (3{,}092.8 - 321.8) \text{ kJ/kg} = 2{,}771.0 \text{ kJ/kg}$
$q_{\text{out}} = (H_3 - H_4) = (2{,}243.1 - 317.6) \text{ kJ/kg} = 1{,}925.5 \text{ kJ/kg}$
$\dot{W}_{\text{net out}} = \dot{m}(q_{\text{in}} - q_{\text{out}}) = (42 \text{ kg/s})(2{,}771.0 - 19{,}25.5) \text{ kJ/kg} = 35{,}511 \text{ kW}$

The thermal efficiency
$\eta_{\text{th}} = 1 - \dfrac{q_{\text{out}}}{q_{\text{in}}} = 0.305 \text{ or } 30.5\%$
The overall plant efficiency: $\eta_{\text{overall}} = \eta_{\text{th}}\eta_{\text{comb}}\eta_{\text{gen}} = (0.305)(0.77)(0.95) = 0.223$
The rate of coal energy supply: $\dot{E}_{\text{coal}} = \dfrac{\dot{W}_{\text{net}}}{\eta_{\text{overall}}} = \dfrac{35{,}511}{0.223} = 159{,}165 \text{ kJ/s}$
Energy of coal (bituminous) = 24,000 kJ/kg (Table 2.8 and Table 2.9)
$\dot{m}_{\text{coal}} = \dfrac{\dot{E}_{\text{coal}}}{\eta_{\text{overall}}} = \dfrac{159{,}165}{24{,}000}\left(\dfrac{1 \text{ ton}}{1{,}000 \text{ kg}}\right) = 0.0066 \text{ ton/s} = 23.9 \text{ ton/h}$
With the increased combustion efficiency and generator efficiency, the required amount of coal is reduced to 23.9 from 36.6 ton/h. This leads to around 35% savings of coal.

9.4.4 Fuel Efficiency of Vehicles

The fuel efficiency of vehicles can be expressed in miles per gallon (mpg) or liters (l) per km. Comparison reveals:

- An average north American mid-size car travels 21 mpg (US) (11 l/100 km) city, 27 mpg (US) (9 l/100 km) highway.
- A modern European mid-size car travels 36 mpg (6.5 l/100 km) city, 47 mpg (5 l/100 km) motorway

Diesel engines generally achieve greater fuel efficiency than gasoline engines. Passenger car diesel engines have energy efficiency of up to 41% but more typically 30%, and petrol engines of up to 37.3%, but more typically 20%. The higher compression ratio is helpful in raising the energy efficiency, but diesel fuel also contains approximately 10% more energy per unit volume than gasoline which contributes to the reduced fuel consumption for a given power output.

Fuel efficiency directly affects emissions causing pollution. Cars can run on a variety of fuel sources, such as gasoline, natural gas, liquefied petroleum gases, biofuel, or electricity. All these create various quantities of atmospheric pollution. A kilogram of carbon produces approximately 3.63 kg of CO_2 emissions. Typical average emissions from combustion of gasoline and diesel are:

- Gasoline combustion emits 19.4 lb CO_2/US gal or (2.32 kg CO_2/l)
- Diesel combustion emits 22.2 lb CO_2/US gal or (2.66 kg CO_2/l)

These values are only the CO_2 emissions of the final forms of fuel products and do not include additional CO_2 emissions created during the drilling, pumping, transportation, and refining steps of the fuel production [11]. Examples 9.18 and 9.19 illustrate the estimation of fuel consumption of a car and show that the conservation in fuel and reduction in emission of CO_2 are significant when the fuel efficiency of car increases.

Example 9.18 Fuel consumption of a car

The overall efficiencies are about 25–28% for gasoline car engines, 34–38% for diesel engines, and 40–60% for large power plants [7]. A car engine with a power output of 120 hp has a thermal efficiency of 24%. Determine the fuel consumption of the car if the fuel has a higher heating value of 20,400 Btu/lb.

Solution:
Assume: the car has a constant power output.
Gasoline car engine:

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{q}_{\text{in}}} \rightarrow \dot{q}_{\text{in}} = \frac{\dot{W}_{\text{net}}}{\eta_{\text{th}}} = \frac{120\,\text{hp}}{0.24}\left(\frac{2{,}545\,\text{Btu/h}}{\text{hp}}\right)$$

$$\dot{q}_{\text{in}} = 1{,}272{,}500\,\text{Btu/hr}$$

Net heating value = higher heating value (1 – 0.1) = 18,360 Btu/lb (approximately)

Fuel consumption = $\dot{q}_{\text{in}}$/net heating value = 1,272,500 Btu/h/18,360 Btu/lb = 69.3 lb/h

Assuming an average gasoline density of 0.75 kg/l:

ρ_{gas} = (0.75 kg/l)(2.2 lb/kg)(l/0.264 gal) = 6.25 lb/gal

Fuel consumption in terms of gallon: (69.3 lb/h)/(6.25 lb/gal) = **11.1 gal/h**
Diesel engine with an efficiency of 36%:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{q}_{in}} \to \dot{q}_{in} = \frac{\dot{W}_{net}}{\eta_{th}} = \frac{120\,\text{hp}}{0.36}\left(\frac{2{,}545\,\text{Btu/h}}{\text{hp}}\right) = 848{,}333\,\text{Btu/h}$$

$\dot{q}_{in} = \mathbf{848{,}333\,Btu/h}$

9.4.5 Energy Conservation While Driving

Some possible energy conservation steps are:

- Speeding, rapid acceleration, and braking waste gas. It can lower your gas mileage by 33% at highway speeds and by 5% around town. Gas mileage usually decreases rapidly at speeds above 60 mph and observing the speed limit may lead to fuel saving of 7–23%.
- An extra 100 pounds in your vehicle could reduce the fuel efficiency by up to 2%.
- Using cruise control helps save gas.
- Fixing a serious maintenance problem, such as a faulty oxygen sensor, can improve your mileage by as much as 40%.
- Gas mileage may be improved by up to 3.3% by keeping your tires inflated to the proper pressure.

The most efficient machines for converting energy to rotary motion are electric motors, as used in electric vehicles. However, electricity is not a primary energy source so the efficiency of the electricity production has also to be taken into account. In the future, hydrogen cars powered either through chemical reactions in a fuel cell that create electricity to drive electrical motors or by directly burning hydrogen in a combustion engine may be commercially available. These vehicles have near zero pollution from the exhaust pipe. Potentially the atmospheric pollution could be minimal, provided the hydrogen is made by electrolysis using electricity from non-polluting sources such as solar, wind, or hydroelectricity. In addi-tion to the energy cost of the electricity or hydrogen production, transmission and/or storage losses to support large-scale use of such vehicles should also be accounted.

Example 9.19 Fuel conservation with a more fuel-efficient car
Assume two cars one with 11 l/100 km city and 9 l/100 km highway, and the other 6.5 l/100 km in city traffic and at 5 l/100 km motorway are used. Estimate the annual fuel saving and emission reduction achieved with the more fuel-efficient car traveling an average 15,000 km per year.

Solution:
Fuel saving for every 100 km city driving in liters = (11 – 6.5) l = 4.5 l
Fuel saving for every 100 km highway driving in liters = (9 – 5) l = 4.0 l

Average saving for 100 km is (4.0 + 4.5) l/2 = 4.2 l
A fuel-efficient car can conserve an average of about 4.2 l gasoline for every 100 km.
For a car driving 15,000 km per year, the amount of fuel conserved would be:
(15,000 km/year) (4.2 l/100 km) = **630 l/year (167 gallon/year)**

Gasoline combustion emits 19.4 lb CO_2/US gal or (2.32 kg CO_2/l)
Annual emission reduction = (2.32 kg CO_2/l) (630 l/year)
= **1,462 kg/year (or 3,294 lb/year)**
Both the conservation in fuel and reduction in emission of CO_2 are significant with increased fuel efficiency of cars globally.

9.4.6 Regenerative Braking

In conventional braking systems, the excess kinetic energy is converted to heat by friction in the brake pads and therefore wasted. Regenerative braking is the conversion of the vehicle's kinetic energy into chemical energy, which is stored in the battery and used in driving again in battery-powered and hybrid gas/electric vehicles. The recovery is around 60% [25]. The advanced algorithms in the motor control the motor torque for both driving and regenerative braking. A torque command is derived from the position of the throttle pedal. The motor controller converts this torque command into the appropriate 3-phase voltage and current waveforms to produce the commanded torque in the motor in the most efficient way. When the torque serves to slow the vehicle then energy is returned to the battery.

Negative torque applied to the rear wheels can cause a car to become unstable since regenerative braking is a source of negative torque. The traction control system limits regenerative braking if the rear wheels start to slip. The control system provides the driver instant positive and negative torque command. Regenerative braking is limited when the batteries are fully charged, and motor controller will limit regenerative torque in this case. It is possible that with the increased use of battery-powered vehicles, a safe regenerative braking will be an efficient way of converting and recovering the kinetic energy.

9.5 Energy Conservation in Electricity Distribution and Smart Grid

A *smart grid* is a form of electricity network using digital technology. Smart grid delivers electricity to consumers to control appliances at homes, optimize power flows, reduce waste, and maximize the use of lowest-cost production resources. The smart grid is envisioned to overlay the ordinary electrical grid with an information and net metering system that includes smart meters. The increased

data transmission capacity has made it possible to apply sensing, measurement and control devices with two-way communications to electricity production, transmission, distribution, and consumption parts of the power grid. These devices could communicate information about grid condition to system users, operators, and automated devices. Therefore, the average consumer can respond dynamically to changes in grid conditions [22].

A smart grid includes an intelligent monitoring system that keeps track of all electricity flowing in the system. It also has the capability of integrating renewable electricity such as solar and wind. When power is least expensive the user can allow the smart grid to turn on selected home appliances such as washing machines or some processes in a factory. At peak times, it could turn off selected appliances to reduce demand [12]. Some smart grid functions are:

1. Motivate consumers to actively participate in operations of the grid.
2. Provide higher quality power that will save money wasted from outages.
3. Accommodate all generation and storage options.
4. Enable electricity markets to flourish by running more efficiently.
5. Enable higher penetration of intermittent power generation sources.

9.5.1 Standby Power

Standby power refers to the electricity consumed by many appliances when they are switched off or in standby mode. The typical power loss per appliance is low (from 1 to 25 W) but when multiplied by the billions of appliances in houses and in commercial buildings, standby losses represent a significant fraction of total world electricity use. Standby power may account for consumption between 7 and 13% of household power consumption. Technical solutions to the problem of standby power exist in the form of a new generation of power transformers that use only 100 mW in standby mode and thus can reduce standby consumption by up to 90%. Another solution is the 'smart' electronic switch that cuts power when there is no load and restores it immediately when required.

9.5.2 Energy Conservation in Lighting

Energy for lighting accounts for about 10% of the household electric bill (see Fig. 9.3). Compact fluorescent bulbs (see Fig. 9.7) use about 75% less energy than standard lighting, produces 75% less heat, and lasts up to 10 times longer. Compact fluorescent bulbs contain a very small amount of mercury sealed within the glass tubing. Although linear fluorescent and compact fluorescent bulbs cost a bit more than incandescent bulbs initially, over their lifetime they are cheaper because of the less electricity they use [26]. Example 9.20 illustrates the energy conservation by using the compact fluorescent bulbs.

Fig. 9.7 Compact fluorescent bulbs use about 75% less energy than standard lighting

Example 9.20 Conservation of energy with compact fluorescent bulbs
Assume that an average residential rate of electricity is \$0.14/kWh and a household consumes about 10,000 kWh per year. If the lighting is provided by compact fluorescent bulbs only, estimate the conservation of energy and saving per year.

Solution:
Assume that 11% of the energy budget of household is for lighting, and compact fluorescent bulbs consume about 75% less energy than standard lighting.

Annual energy use and cost with standard lighting:
(10,000 kWh/year) (0.11) = 1,100 kW/year
(1,100 kW/year)(\$0.14/kWh) = \$154/year

Annual energy use and cost with compact fluorescent bulbs:
(1,100 kW/year) (1 – 0.75) = 275 kWh/year
(275 kWh/year) (\$0.14/kWh) = \$38.5/year

Annual energy and cost savings:
(1,100 – 275) kWh = **825 kWh**
(154 – 38.5)\$/year = **\$115.5/year**

Conservation of energy and cost with compact fluorescent bulbs are.

9.5.3 Energy Harvesting

Despite the high initial costs, energy harvesting is often more effective in cost and resource utilization when done on a group of houses, co-housing, local district, or village rather than an individual basis. This leads to the reduction of electrical transmission and electricity distribution losses, which may be about 7% of the energy transferred. The net zero fossil energy consumption requires locations of geothermal, microhydro, solar, and wind resources to sustain the concept. One of the key areas of debate in zero energy building design is over the balance between energy conservation and the distributed point-of-use harvesting of renewable energy such as solar and wind energy. Wide acceptance of zero or close to zero energy building technology may require more government incentives, building code regulations, or significant increases in the cost of conventional energy [26, 13, 4]. Some benefits of energy harvesting are:

- Isolation for building owners from future energy price increases.
- Increased comfort due to more-uniform interior temperatures.
- Reduced total cost of ownership due to improved energy efficiency.

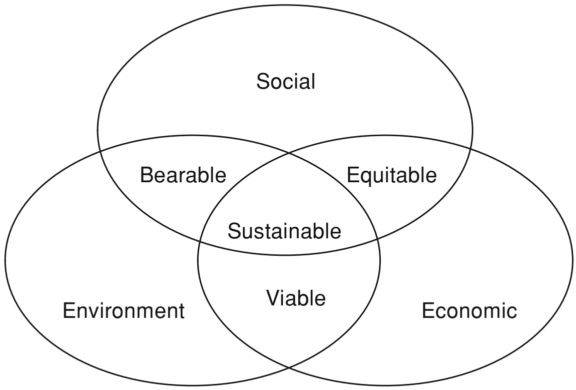


Fig. 9.8 Three elements of sustainability [23, 24]

9.6 Conservation of Energy and Sustainability

Sustainability is improving the quality of human life while living within the carrying capacity of supporting ecosystems. The overall driver of human impact on earth systems is the destruction of biophysical resources, and especially, the earth's ecosystems. Sustainability formulation attempts to explain the environmental impact of human consumption I in terms of three components: population P, levels of consumption that is affluence A, and impact per unit of resource use, which is termed as technology T, and presented by Daly and Farley [8], Hak et al. [15] and Soederbaum [24]

$$I = P \times A \times T \tag{9.14}$$

Sustainability measurement is used as the quantitative basis for the sustainability of environmental, social, and economic domains (see Fig. 9.8). A challenge to sustainability is the combination of population increase in the developing world and unsustainable consumption levels in the developed world. Some sustainability principles are:

- Reduce dependence on natural deposits such as fossil fuels, ores, and minerals.
- Reduce dependence on synthetic chemicals and other unnatural substances.
- Meet human needs fairly.

Zero energy building and green building are two efforts toward sustainability. The goal of green building and sustainable architecture is to use resources more efficiently and reduce a building's negative impact on the environment. Zero energy buildings achieve the goal by completely or very significantly reducing

energy use and greenhouse gas emissions for the life of the building. Zero energy buildings may or may not be considered "green" in all areas, such as reducing waste, and using recycled building materials. However, zero energy buildings may have a much lower ecological impact compared with other 'green' buildings that require imported energy and/or fossil fuel. Green building certification programs require reducing the use of energy considerably [14].

9.7 Exergy Conservation and Exergy

Energy conservation through exergy concepts for some steady-state flow processes are [6, 9]:

- Exergy is lost by irreversibilities associated with pressure drops, fluid friction, and stream-to-stream heat transfer due to temperature differences.
- In a steam power plant, exergy transfers are due to work and heat, and exergy is lost within the control volume.
- In a waste-heat recovery system, we might reduce the heat transfer irreversibility by designing a heat recovery steam generator with a smaller stream-to-stream temperature difference, and/or reduce friction by designing a turbine with a higher efficiency.
- A cost-effective design may result from a consideration of the trade-offs between possible reduction of exergy loss and potential increase in operating cost.

9.8 Energy Recovery on Utilities Using Pinch Analysis

A process may have available hot and cold streams. When the hot and cold streams exchange heat between them, heat is recovered and the hot and cold utility requirements may be minimized. Pinch analysis yields optimum energy integration of process heat and utilities by matching the hot and cold streams with a network of heat exchangers. In the pinch analysis, hot and cold streams can only exchange energy up to a minimum allowable temperature difference $\Delta T_{\min}$, which is called the pinch point leading to the minimum driving force for heat transfer [9, 17].

An increase in $\Delta T_{\min}$ causes higher energy and lower capital costs (a smaller heat exchanger area as seen in Fig. 9.9). For example, an increase of 5°C from a value of $\Delta T_{\min} = 10°C$ decreases the heat exchanger area by 11%, and increases the required minimum energy by about 9%. To find the optimum value of $\Delta T_{\min}$, the total annual cost is plotted against it. An optimum $\Delta T_{\min}$ appears at the

Fig. 9.9 Optimum ΔT_{min} from energy cost and capital cost changes

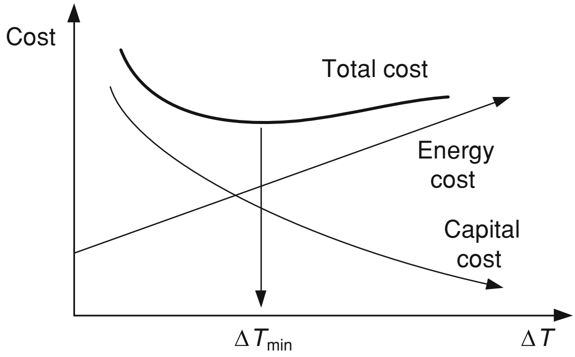
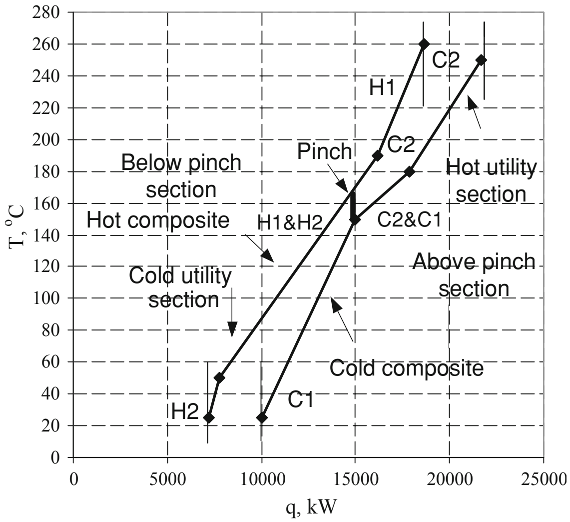


Fig. 9.10 Hot and cold composite curves for a ΔT_{min} of 20°C using two hot (H) streams and two cold (C) streams



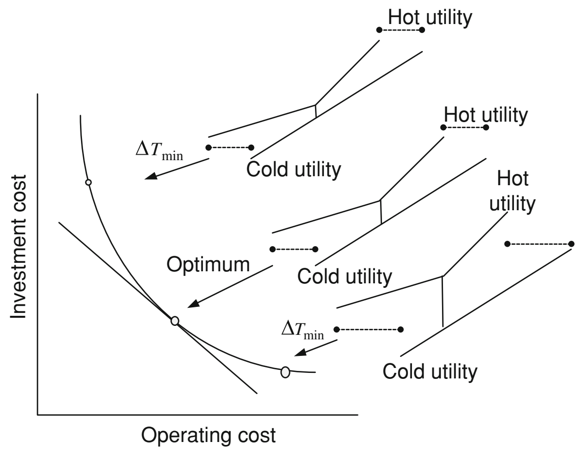
minimum total annual cost of energy and capital. The optimum value for ΔT_{min} is generally in the range of 3–40°C and needs to be established for a process.

9.8.1 Composite Curves

Temperature-enthalpy diagrams called *composite curves* represent the thermal characteristics of hot and cold streams and the amount of heat transferred between them (see Fig. 9.10). The enthalpy change rate for each stream is

$$\dot{q} = \dot{m}\Delta H = \dot{m}C_p\Delta T = MC\Delta T \tag{9.15}$$

Fig. 9.11 Principle of pinch technology



where ΔH is the enthalpy change rate, $\dot{m}$ is the mass flow rate, C_p is the heat capacity, ΔT is the temperature change in a stream, and MC is the heat capacity rate $\dot{m}C_p$. The enthalpy change rates are added over each temperature interval that includes one or more of the streams. This leads to hot and cold composite curves of the streams shown in Fig. 9.10. If $\dot{m}C_p$ is constant, q versus T would be a straight line

$$\Delta T = \frac{1}{\dot{m}C_p}\dot{q} \tag{9.16}$$

Enthalpy changes rather than absolute enthalpies are estimated, and the horizontal location of a composite line on the diagram is arbitrarily fixed. One of the two curves is moved horizontally until the distance of the closest vertical approach matches the selected value of $\Delta T_{\min}$. The pinch point is the location of $\Delta T_{\min}$ on the adjusted composite diagram where the hot and cold curves most closely approach each other in temperature in a vertical direction. The overshoot of the hot composite curve represents the minimum cold utility ($q_{c,\ \min}$) required, and the overshoot of the cold composite curve represents the minimum hot utility ($q_{h,\ \min}$) required (see Figs. 9.10 and 9.11). Example 9.21 illustrates the use of pinch analysis in processing heat integration and minimizing the hot and cold utilities.

Above the pinch, only the hot utility is required, while only the cold utility is required below the pinch. These diagrams enable engineers to minimize the expensive utilities. Pinch analysis may also lead to optimum integration of evaporators, condensers, furnaces, and heat pumps by reducing the utility requirements. Pinch analysis is utilized widely in industry leading to considerable energy savings. Figure 9.11 displays the importance of minimum temperature approach between available hot and cold utilities. As the values of $\Delta T_{\min}$ increase the amount of hot and cold utilities increase together with the operating cost. On the other hand, as the values of $\Delta T_{\min}$ decreases, the investment cost increases. So these two opposing costs should be optimized as seen in Fig. 9.9.

Example 9.21 Energy conservation by the pinch analysis

In a process, available hot and cold process streams and their heat capacities are shown below.

Hot and Cold Process Stream Conditions

Streams		T_{in} (°C)	T_{out} (°C)	$C = \dot{m}C_p$(kW/°C)	$q = \dot{m}C_p\Delta T$(kW)
C1	Cold 1	25	180	40	6,200
C2	Cold 2	150	250	55	5,500
H1	Hot 1	260	50	35	−7,350
H2	Hot 2	190	25	25	−4,125

Construct the balanced composite curves for the process with $\Delta T_{min} = 20$ and 10°C, and compare the amounts of hot and cold utilities needed

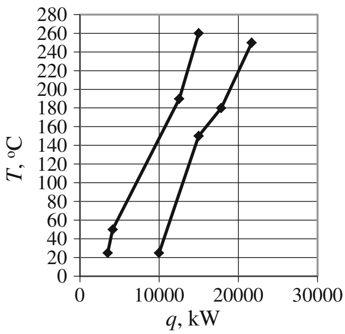
Solution:

Assume that heat capacities of hot and cold streams are constant.

A starting enthalpy change rate is chosen as 10,000 kW at 25°C for the streams to be heated, while for the streams to be cooled, the base value chosen is 15,000 kW at 260°C. Initial temperature interval with overlaps is shown below:

Initial temperature interval					Initial enthalpy selection	
Streams	Temperature interval (°C)		C (kW/°C)	q (kW)	T (°C)	q (kW)
					25	10,000(arbitrary)
C1	25	150	40	5,000	150	15,000
C1&C2	150	180	95	2,850	180	17,850
C2	180	250	55	3,850	250	21,700
				11,700		
					260	15,000(arbitrary)
H1	260	190	35	−2,450	190	12,550
H2&H1	190	50	60	−8,400	50	4,150
H2	50	25	25	−625	25	3,525
				−11,475		

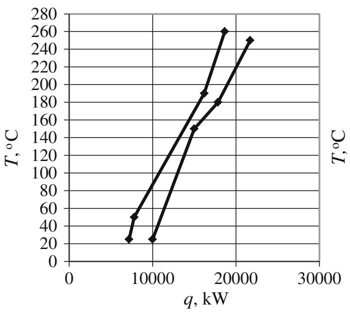
This table may be converted to the hot and cold composite curves below



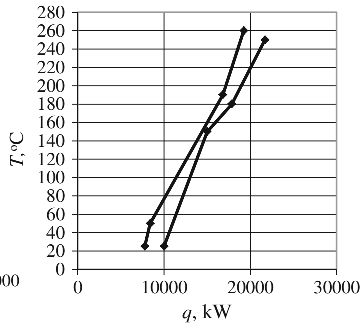
Here the composite curves move to each other so that at the pinch point minimum temperature difference would $\Delta T_{min} = 20°C$, the diagram is called a *balanced composite diagram.*

Revised temperature interval					Revised enthalpy selection	
Stream	Required temperature interval (°C)		C (kW/°C)	q (kW)	q (kW)	T (°C)
					10,000	25
C1	25	150	40	5,000	15,000	150
C1&C2	150	180	95	2,850	17,850	180
C2	180	250	55	3,850	21,700	250
				11,700		
					18,650	260
H1	260	190	35	−2,450	16,200	190
H2&1	190	50	60	−8,400	7,800	50
H2	50	25	25	−625	7,175	25
				−11,475		

Composite diagram with $\Delta T_{min} = 20$ and 10°C approach temperatures are shown below



$\Delta T_{min} = 20°C$



$\Delta T_{min} = 10°C$

For approach temperatures of $\Delta T_{min} = 10$ and 20°C estimated minimum hot and cold utilities are:

Cold utility (i.e. cooling water): $q_{cold,\ min}$ (kW)	2,225	2,825
Hot utility (i.e. steam): $q_{hot,\ min}$ (kW)	2,450	3,050
Approach temperatures: ΔT_{min} (°C)	10	20

Energy savings = (3,050 – 2,450) kW = 600 kW
Energy savings = (2,825 – 2,225) kW = 600 kW

This simple analysis shows that the smaller approach temperature reduces the utilities needed considerably.

Problems

9.1. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 9$. The fresh air temperature at the compressor inlet is 295 K. The air temperature at the inlet of the turbine is 1,300 K. The cycle operates with a compressor efficiency of 80% and a turbine efficiency of 80%. The flow rate gas is 3 kg/s and unit cost of fuel is $0.15/kWh. The cycle operates 360 days per year.
(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.
(b) If the power plant operates with a regenerator with an effectiveness of 0.80, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.2. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 9$. The fresh air temperature at the compressor inlet is 300 K. The air temperature at the inlet of the turbine is 1,300 K. The cycle operates with a compressor efficiency of 85% and a turbine efficiency of 85%. The flow rate gas is 5 kg/s and unit cost of fuel is $0.15/kWhr. The cycle operates 360 days per year.
(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.
(b) If the power plant operates with a regenerator with an effectiveness of 0.80, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.3. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 8$. The fresh air temperature at the compressor inlet is 300 K. The air temperature at the inlet of the turbine is 1,350 K. The cycle operates with a compressor efficiency of 85% and a turbine efficiency of 80%. The flow rate gas is 5 kg/s and unit cost of fuel is $0.11/kWh. The cycle operates 360 days per year.
(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.
(b) If the power plant operates with a regenerator with an effectiveness of 0.7, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.4. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 15$. The fresh air temperature at the compressor inlet is 290 K. The air temperature at the inlet of the turbine is 1,400 K. The cycle operates

with a compressor efficiency of 90% and a turbine efficiency of 80%. The flow rate gas is 4.5 kg/s and unit cost of fuel is \$0.16/kWh. The cycle operates 360 days per year.

(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.

(b) If the power plant operates with a regenerator with an effectiveness of 0.75, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.5. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 14$. The fresh air temperature at the compressor inlet is 290 K. The air temperature at the inlet of the turbine is 1,400 K. The cycle operates with a compressor efficiency of 90% and a turbine efficiency of 80%. The flow rate gas is 4.5 kg/s and unit cost of fuel is \$0.16/kWh. The cycle operates 360 days per year.

(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.

(b) If the power plant operates with a regenerator with an effectiveness of 0.75, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.6. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 7.5$. The fresh air temperature at the compressor inlet is 290 K. The air temperature at the inlet of the turbine is 1,250 K. The cycle operates with a compressor efficiency of 90% and a turbine efficiency of 85%. The flow rate gas is 6.5 kg/s and unit cost of fuel is \$0.10/kWh. The cycle operates 360 days per year.

(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.

(b) If the power plant operates with a regenerator with an effectiveness of 0.75, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.7. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 11.0$. The fresh air temperature at the compressor inlet is 290 K. The air temperature at the inlet of the turbine is 1,350 K. The cycle operates with a compressor efficiency of 85% and a turbine efficiency of 80%. The flow rate gas is 6.0 kg/s and unit cost of fuel is \$0.10/kWh. The cycle operates 360 days per year.

(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.

(b) If the power plant operates with a regenerator with an effectiveness of 0.76, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.8. A power plant is operating on an ideal Brayton cycle with a pressure ratio of $r_p = 10.0$. The fresh air temperature at the compressor inlet is 290 K. The air temperature at the inlet of the turbine is 1,350 K. The cycle

operates with a compressor efficiency of 85% and a turbine efficiency of 80%. The flow rate gas is 6.0 kg/s and unit cost of fuel is \$0.10/kWh. The cycle operates 360 days per year.

(a) Using the standard-air assumptions, determine the thermal efficiency of the cycle.

(b) If the power plant operates with a regenerator with an effectiveness of 0.76, determine the thermal efficiency of the cycle and annual conservation of fuel.

9.9. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 3,500 kPa and 400°C. Discharge pressure of the steam from the turbine is 78.5 kPa.

(a) Determine the thermal efficiency of the cycle.

(b) If the pressure of the discharge steam is reduced to 15 kPa determine the thermal efficiency.

(c) Determine the annual saving if the unit cost of electricity is \$0.15/kWh.

9.10. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 35 kg/s. The steam enters the turbine at 4,000 kPa and 350°C. Discharge pressure of the steam from the turbine is 101.3 kPa.

(a) Determine the thermal efficiency of the cycle.

(b) If the pressure of the discharge steam is reduced to 15 kPa determine the thermal efficiency.

(c) Determine the annual saving if the unit cost of electricity is \$0.12/kWh.

9.11. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 30 kg/s. The steam enters the turbine at 3,000 kPa and 400°C. Discharge pressure of the steam from the turbine is 67.5 kPa.

(a) Determine the thermal efficiency of the cycle.

(b) If the pressure of the discharge steam is reduced to 15 kPa determine the thermal efficiency.

(c) Determine the annual saving if the unit cost of electricity is \$0.12/kWh.

9.12. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 30 kg/s. The steam enters the turbine at 2,500 kPa and 300°C. Discharge pressure of the steam from the turbine is 62.5 kPa.

(a) Determine the thermal efficiency of the cycle.

(b) If the pressure of the discharge steam is reduced to 15 kPa determine the thermal efficiency.

(c) Determine the annual saving if the unit cost of electricity is \$0.12/kWh.

9.13. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 35 kg/s. The steam enters the turbine at 3,000 kPa and 350°C. Discharge pressure of the steam from the turbine is 78.5 kPa.

(a) Determine the thermal efficiency of the cycle.

(b) If the pressure of the boiler is increased to 10,000 kPa while maintaining the turbine inlet temperature at 350°C, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is \$0.12/kWh.

9.14. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 42 kg/s. The steam enters the turbine at 2,500 kPa and 300°C. Discharge pressure of the steam from the turbine is 15.0 kPa.
(a) Determine the thermal efficiency of the cycle.
(b) If the pressure of the boiler is increased to 9,000 kPa while maintaining the turbine inlet temperature at 300°C, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is \$0.12/kWh.

9.15. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 50 kg/s. The steam enters the turbine at 4,000 kPa and 400°C. Discharge pressure of the steam from the turbine is 15.0 kPa.
(a) Determine the thermal efficiency of the cycle.
(b) If the pressure of the boiler is increased to 11,000 kPa while maintaining the turbine inlet temperature at 400°C, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is \$0.12/kWh.

9.16. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 35 kg/s. The steam enters the turbine at 3,500 kPa and 300°C. Discharge pressure of the steam from the turbine is 78.5 kPa.
(a) Determine the thermal efficiency of the cycle.
(b) If the temperature of the boiler is increased to 500°C while maintaining the pressure at 3,500 kPa, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is \$0.15/kWh.

9.17. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 40 kg/s. The steam enters the turbine at 3,000 kPa and 300°C. Discharge pressure of the steam from the turbine is 15 kPa.
(a) Determine the thermal efficiency of the cycle.
(b) If the temperature of the boiler is increased to 500°C while maintaining the pressure at 3,000 kPa, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is \$0.15/kWh.

9.18. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 40 kg/s. The steam enters the turbine at 6,000 kPa and 350°C. Discharge pressure of the steam from the turbine is 15 kPa.
(a) Determine the thermal efficiency of the cycle.
(b) If the temperature of the boiler is increased to 500°C while maintaining the pressure at 6,000 kPa, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is \$0.15/kWh.

9.19. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 40 kg/s. The steam enters the turbine at 9,000 kPa and 400°C. Discharge pressure of the steam from the turbine is 15 kPa.
(a) Determine the thermal efficiency of the cycle.
(b) If the temperature of the boiler is increased to 550°C while maintaining the pressure at 9,000 kPa, determine the thermal efficiency.
(c) Determine the annual saving if the unit cost of electricity is $0.15/kWh.

9.20. Estimate the maximum possible efficiency for parts (a) and (b) in Problem 9.18 and compare them with those obtained in parts (a) and (b) in Problem 9.18.

9.21. Estimate the maximum possible efficiency for parts (a) and (b) in Problem 9.19 and compare them with those obtained in parts (a) and (b) in Problem 9.19.

9.22. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 3,000 kPa and 400°C. Discharge pressure of the steam from the turbine is 78.5 kPa.
(a) If the pressure of the boiler is increased to 9,000 kPa while maintaining the turbine inlet temperature at 400°C, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is $0.15/kWh.

9.23. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 4,000 kPa and 400°C. Discharge pressure of the steam from the turbine is 15 kPa.
(a) If the pressure of the boiler is increased to 9,500 kPa while maintaining the turbine inlet temperature at 400°C, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is $0.15/kWh.

9.24. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 5,000 kPa and 350°C. Discharge pressure of the steam from the turbine is 15 kPa.
(a) If the pressure of the boiler is increased to 10,000 kPa while maintaining the turbine inlet temperature at 350°C, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is $0.15/kWh.

9.25. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 9,800 kPa and 350°C. Discharge pressure of the steam from the turbine is 78.5 kPa.
(a) If the temperature of the boiler is increased to 600°C while maintaining the pressure at 9,800 kPa, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is $0.16/kWh.

9.26. A steam power plant is operating on the simple ideal Rankine cycle. The steam mass flow rate is 20 kg/s. The steam enters the turbine at 8,000 kPa and 325°C. Discharge pressure of the steam from the turbine is 78.5 kPa.
(a) If the temperature of the boiler is increased to 550°C while maintaining the pressure at 8,000 kPa, determine the thermal efficiency.
(b) Determine the annual saving if the unit cost of electricity is $0.16/kWh.

9.27. Estimate the maximum possible efficiency for parts (a) and (b) in Problem 9.25 and compare them with those obtained in parts (a) and (b) in Problem 9.25.

9.28. Estimate the maximum possible efficiency for parts (a) and (b) in Problem 9.26 and compare them with those obtained in parts (a) and (b) in Problem 9.26.

9.29. Air with a flow rate of 4 kg/s is compressed in a steady-state and reversible process from an inlet state of 100 kPa and 300 K to an exit pressure of 1,000 kPa. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.20/kWh and the compressor is operated 360 days per year.

9.30. Air is compressed in a steady-state and reversible process from an inlet state of 100 kPa and 285 K to an exit pressure of 800 kPa. The mass flow rate of air is 8 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.35$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.35$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.08/kWh and the compressor is operated 360 days per year.

9.31. Air is compressed in a steady-state and reversible process from an inlet state of 110 kPa and 290 K to an exit pressure of 900 kPa. The mass flow rate of air is 10 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.1/kWh and the compressor is operated 360 days per year.

9.32. Air is compressed in a steady-state and reversible process from an inlet state of 110 kPa and 290 K to an exit pressure of 900 kPa. The mass flow rate of air is 10 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.2$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.2$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.12/kWh and the compressor is operated 360 days per year.

9.33. Air is compressed in a steady-state and reversible process from an inlet state of 100 kPa and 290 K to an exit pressure of 900 kPa. The mass flow rate of air is 5 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.25$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.25$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.11/kWh and the compressor is operated 360 days per year.

9.34. Air is compressed in a steady-state and reversible process from an inlet state of 100 kPa and 290 K to an exit pressure of 900 kPa. The mass flow rate of air is 3.5 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling

using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.09/kWh and the compressor is operated 360 days per year.

9.35. Natural gas contains mostly the methane gas. In a steady-state and reversible process, natural gas is compressed from an inlet state of 100 kPa and 290 K to an exit pressure of 1,000 kPa. The mass flow rate of natural gas is 8 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.08/kWh and the compressor is operated 360 days per year.

9.36. Natural gas contains mostly the methane gas. In a steady-state and reversible process, natural gas is compressed from an inlet state of 100 kPa and 290 K to an exit pressure of 900 kPa. The mass flow rate of natural gas is 5 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.2$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.2$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.08/kWh and the compressor is operated 360 days per year.

9.37. In a steady-state and reversible process, propane gas is compressed from an inlet state of 100 kPa and 300 K to an exit pressure of 900 kPa. The mass flow rate of propane is 3 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved work by intercooling and electricity per year if the unit cost of electricity is \$0.08/kWh and the compressor is operated 360 days per year.

9.38. In a steady-state and reversible process, hydrogen gas is compressed from an inlet state of 100 kPa and 300 K to an exit pressure of 1,100 kPa. The mass flow rate of hydrogen is 3 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved work by intercooling and electricity per year if the unit cost of electricity is \$0.12/kWh and the compressor is operated 360 days per year.

9.39. In a steady-state and reversible process, carbon dioxide gas is compressed from an inlet state of 100 kPa and 290 K to an exit pressure of 1,000 kPa. The mass flow rate of carbon dioxide is 4 kg/s. Estimate the work for (a) polytropic compression with $\gamma = 1.3$, and (b) ideal two-stage polytropic compression with intercooling using the same polytropic exponent of $\gamma = 1.3$, (c) estimate conserved compression work by intercooling and electricity per year if the unit cost of electricity is \$0.16/kWh and the compressor is operated 360 days per year.

9.40. An adiabatic compressor is used to compress air from 100 kPa and 290 K to 900 kPa at a steady-state operation. The isentropic efficiency of the compressor is 80%. The air flow rate is 0.55 kg/s. Determine the minimum and actual power needed by the compressor.

9.41. An adiabatic compressor is used to compress air from 100 kPa and 290 K to 1,100 kPa at a steady-state operation. The isentropic efficiency of the compressor is 80%. The air flow rate is 0.35 kg/s. Determine the minimum and actual power needed by the compressor.

9.42. An adiabatic compressor is used to compress air from 100 kPa and 290 K to 1,400 kPa at a steady-state operation. The isentropic efficiency of the compressor is 85%. The air flow rate is 0.5 kg/s. Determine the minimum and actual power needed by the compressor.

9.43. An adiabatic compressor is used to compress air from 100 kPa and 290 K to 1,600 kPa at a steady-state operation. The isentropic efficiency of the compressor is 83%. The air flow rate is 0.4 kg/s. Determine the minimum and actual power needed by the compressor.

9.44. Estimate the power conservation when an electric motor with an efficiency of 78% is replaced with another motor operating at 88% efficiency. Both the motors drive compressor and must deliver a power of 24 kW for an average 2,500 h/year and the unit cost of electricity is $0.18/kWh.

9.45. Estimate the power conservation when an electric motor with an efficiency of 74% is replaced with another motor operating at 89% efficiency. Both the motors drive compressor and must deliver a power of 36 kW for an average 8,000 h/year and the unit cost of electricity is $0.14/kWh.

9.46. Estimate the power conservation when an electric motor with an efficiency of 74% is replaced with another motor operating at 89% efficiency. Both the motors drive compressor and must deliver a power of 18 kW for an average 80 h per day and the unit cost of electricity is $0.15/kWh.

9.47. A cryogenic manufacturing plant handles liquid methane at 115 K and 5,000 kPa at a rate of 0.15 m^3/s. In the plant a throttling valve reduces the pressure of liquid methane to 2,000 kPa. A new process considered replaces the throttling valve with a turbine in order to produce power while reducing the pressure. Using the data for the properties of liquid methane below estimate (a) the power that can be produced by the turbine, and (b) the savings in electricity usage per year if the turbine operates 360 days per year with a unit cost of electricity at $0.18/kWh.

T (K)	P (kPa)	H (kJ/kg)	S (kJ/kg K)	C_p (kJ/kg K)	ρ (kg/m^3)
110	1,000	209.0	4.875	3.471	425.8
110	2,000	210.5	4.867	3.460	426.6
110	5,000	215.0	4.844	3.432	429.1
120	1,000	244.1	5.180	3.543	411.0
120	2,000	245.4	5.171	3.528	412.0
120	5,000	249.6	5.145	3.486	415.2

Source Cengel and Turner [7]

9.48. A cryogenic manufacturing plant handles liquid methane at 115 K and 5,000 kPa at a rate of 0.2 m^3/s. In the plant a throttling valve reduces the pressure of liquid methane to 2,000 kPa. A new process considered replaces the throttling valve with a turbine in order to produce power while reducing the pressure. Using the data for the properties of liquid methane given in Problem 9.47, estimate (a) the power that can be produced by the turbine, (b) the savings in electricity usage per year if the turbine operates 300 days per year with a unit cost of electricity at $0.15/kWh.

9.49. A heat pump is used to heat a house and maintain it at 18°C. On a day where the outside temperature is −2°C, the house is losing heat at a rate of 79,200 kJ/h. The heat pump operates with a coefficient of performance (COP) of 3.5. Determine (a) power needed by the heat pump, (b) the rate of heat absorbed from the surrounding cold air.

9.50. A heat pump is used to heat a house and maintain it at 20°C. On a day where the outside temperature is 0°C, the house is losing heat at a rate of 34,500 kJ/h. The heat pump operates with a coefficient of performance (COP) of 3.0. Determine (a) power needed by the heat pump, (b) the rate of heat absorbed from the surrounding cold air.

9.51. A heat pump is used to heat a house and maintain it at 20°C. On a day where the outside temperature is 4°C, the house is losing heat at a rate of 65,500 kJ/h. The heat pump operates with a coefficient of performance (COP) of 3.9. Determine (a) power needed by the heat pump, (b) the rate of heat absorbed from the surrounding cold air.

9.52. A Carnot heat pump is used to heat a house during the winter. The house is maintained at 20°C. The house is estimated to be losing heat at a rate of 108,000 kJ/h when the outside temperature is −4°C. Determine the minimum power needed by the heat pump and the rate of heat absorbed from the surrounding cold air.

9.53. A Carnot heat pump is used to heat a house during the winter. The house is maintained at 20°C. The house is estimated to be losing heat at a rate of 78,000 kJ/h when the outside temperature is 2°C. Determine the minimum power needed by the heat pump and the rate of heat absorbed from the surrounding cold air.

9.54. Estimate the cost of electricity for a 10,000 Btu/h (3,000 W) air-conditioning unit operating, with a SEER of 10 Btu/Wh. The unit is used for a total of 1,500 h during an annual cooling season and the unit cost of electricity is $0.16/kWh.

9.55. Estimate the cost of electricity for a 12,000 Btu/h air-conditioning unit operating with a SEER of 14 Btu/Wh. The unit is used for a total of 2,500 h during an annual cooling season and the unit cost of electricity is $0.15/kWh.

9.56. Estimate the cost of electricity for a 9,000 Btu/h air-conditioning unit operating, with a SEER of 12 Btu/Wh. The unit is used for a total of 2,000 h during an annual cooling season and the unit cost of electricity is $0.18/kWh.

9.57. (a) Estimate the annual cost of electric power consumed by a 6 ton air conditioning unit operating for 1,000 h/year with a SEER rating of 10 and a power cost of \$0.14/kWh.
(b) Estimate the value of EER for hot and cold temperatures of 20 and -4°C, respectively.

9.58. (a) Estimate the annual cost of electric power consumed by a 4 ton air-conditioning unit operating for 2,500 h/year with a SEER rating of 12 and a power cost of \$0.18/kWh.
(b) Estimate the value of EER for hot and cold temperatures of 21 and -10°C, respectively.

9.59. (a) Estimate the annual cost of electric power consumed by a 9 ton air-conditioning unit operating for 3,000 h/year with a SEER rating of 14 and a power cost of \$0.18/kWh.
(b) Estimate the value of EER for hot and cold temperatures of 21 and -5°C, respectively.

9.60. A 4 ton current residential air conditioner operates with a SEER rating of 10. This unit will be replaced with a newer unit operating with a SEER rating of 22. The unit operates 130 days with an average 10 h per day. Average inside and outside temperatures are 20 and -4°C, respectively. The unit cost of energy is \$0.15/kWh. Estimate the savings in the cost of electricity and the maximum energy efficiency ratio.

9.61. A 4 ton current residential air conditioner operates with a SEER rating of 10. This unit will be replaced with a newer unit operating with a SEER rating of 22. The unit operates 120 days with an average 9 h per day. Average inside and outside temperatures are 20 and -0°C, respectively. The unit cost of energy is \$0.17/kWh. Estimate the savings in the cost of electricity and the maximum energy efficiency ratio.

9.62. A 4 ton current residential air conditioner operates with a SEER rating of 10. This unit will be replaced with a newer unit operating with a SEER rating of 20. The unit operates 120 days with an average 7 h per day. Average inside and outside temperatures are 22 and -10°C, respectively. The unit cost of energy is \$0.19/kWh. Estimate the savings in the cost of electricity and the maximum energy efficiency ratio.

9.63. The efficiency of an open burner is around 70% for electric heater units and 40% for natural gas units. We operate a 4-kW electric burner at a location where the unit costs of electricity and natural gas are \$0.1/kWh and \$0.60/therm, respectively. Estimate the rate of energy consumption by the burner and unit costs of the utilized energy for both electric and gas burners.

9.64. The efficiency of an open burner is around 72% for electric heater units and 39% for natural gas units. We operate a 6-kW electric burner at a location where the unit costs of electricity and natural gas are \$0.1/kWh and \$0.60/therm, respectively. Estimate the rate of energy consumption by the burner and unit costs of the utilized energy for both electric and gas burners.

9.65. The efficiency of an open burner is around 69% for electric heater units and 42% for natural gas units. We operate a 10-kW electric burner at a location

where the unit costs of electricity and natural gas are \$0.1/kWh and \$0.60/therm, respectively. Estimate the rate of energy consumption by the burner and unit costs of the utilized energy for both electric and gas burners.

9.66. An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The power output is 60 MW. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.70 and the generator efficiency is 0.9, determine the overall plant efficiency and the amount of coal supplied per hour.

9.67. An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The power output is 60 MW. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.70 and the generator efficiency is 0.9, determine the overall plant efficiency and the amount of coal supplied per hour.

9.68. An adiabatic turbine is used to produce electricity by expanding a superheated steam at 5,800 kPa and 400°C. The power output is 55 MW. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.72 and the generator efficiency is 0.9, determine the overall plant efficiency and the amount of coal supplied per hour.

9.69. An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The steam flow rate is 42 kg/s. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.75 and the generator efficiency is 0.90, determine the overall plant efficiency and the amount of coal supplied per hour.

9.70. An adiabatic turbine is used to produce electricity by expanding a superheated steam at 4,100 kPa and 350°C. The steam flow rate is 42 kg/s. The steam leaves the turbine at 40 kPa and 100°C. If the combustion efficiency is 0.75 and the generator efficiency is 0.90, determine the overall plant efficiency and the amount of coal supplied per hour.

9.71. The overall efficiencies are about 25–28% for gasoline car engines, 34–38% for diesel engines, and 40–60% for large power plants (Çengel and Turner 2004). Compare the energy necessary for gasoline and diesel engines. The efficiency for the diesel is 36%. A car engine with a power output of 240 hp has a thermal efficiency of 24%. Determine the fuel consumption of the car if the fuel has a higher heating value of 20,400 Btu/lb.

9.72. The overall efficiencies are about 25–28% for gasoline car engines, 34–38% for diesel engines, and 40–60% for large power plants (Çengel and Turner 2004). Compare the energy necessary for gasoline and diesel engines. The efficiency for the diesel is 35%. A car engine with a power output of 180 hp has a thermal efficiency of 26%. Determine the fuel consumption of the car if the fuel has a higher heating value of 20,400 Btu/lb.

9.73. Fuel consumption of the two cars are one with 11 l/100 km city and 9 l/100 km highway, and the other 6.5 l/100 km in city traffic and at 5 l/100 km highway. Estimate the annual fuel saving and emission

reduction achieved with the more fuel-efficient car traveling an average 7,500 km per year.

9.74. Fuel consumption of the two cars are one with 10 l/100 km city and 8 l/100 km highway, and the other 6.0 l/100 km in city traffic and at 5 l/100 km highway. Estimate the annual fuel saving and emission reduction achieved with the more fuel-efficient car traveling an average 10,000 km per year.

9.75. Fuel consumption of the two cars are one with 12 l/100 km city and 9 l/100 km highway, and the other 7.0 l/100 km in city traffic and at 6 l/100 km highway. Estimate the annual fuel saving and emission reduction achieved with the more fuel-efficient car traveling an average 12,000 km per year.

9.76. Assume that an average residential rate of electricity is \$0.14/kWh and a household consumes about 5,000 kWh per year. If the lighting is provided

Streams		T_{in} (°C)	T_{out} (°C)	$C = \dot{m}C_p$(kW/°C)
C1	Cold 1	20	180	40
C2	Cold 2	160	250	55
H1	Hot 1	280	60	35
H2	Hot 2	190	20	25

Construct the balanced composite curves for the process with $\Delta T_{min} = 20°C$ and $\Delta T_{min} = 10°C$, and compare the amounts of hot and cold utilities needed

by compact fluorescent bulbs only, estimate the conservation of energy and saving per year

9.77. Assume that an average residential rate of electricity is \$0.16/kWh and a household consumes about 14,000 kWh per year. If the lighting is provided by compact fluorescent bulbs only, estimate the conservation of energy and saving per year

9.78. In a process, available hot and cold process streams and their heat capacities are shown below.

Hot and Cold Process Stream Conditions

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